III-1 Consequences of Flooding

Introduction

Flood water can be one of the most destructive forces on earth, especially if caused by an event that unexpectedly overwhelms an existing flood defense 1or by catastrophic breach of a dam or levee. Recent events, such as flooding caused by Hurricane Katrina and the tsunami in Japan, have caused thousands of people to lose their life and unknown billions of dollars in damages. By the same token, dozens of floods (some from similarly unexpected events like a dam or levee breach) occur every year with no resulting loss of life and relatively minimal property damage.

Although flooding can have many types of severe consequences, including economic, social, cultural, and environmental, the primary objective of Reclamation's dam safety program and USACE's dam and levee safety programs are to manage the risk to the public who rely on those structures, and to keep them reasonably safe from flooding. Thus, reducing the risk associated with loss of life is paramount. The safety programs of both agencies treat life loss separately from economic and other considerations. Decisions as to whether invest in dam or levee improvements are based primarily on risk to life by applying the concept of tolerable risks. Since informed decisions based on tolerable risk require estimates of loss of life for potential flood events, the focus of this chapter is on estimating loss of life. Estimation of the magnitude of life loss resulting from a flood requires consideration of the following factors:

- Understanding of the population at risk in the potentially impacted area
- Warning and evacuation assumptions for that population at risk
- Flood characteristics including extents, depths, velocities, and arrival time (can be heavily influence by failure mode and breach parameters)
- Estimation of fatality rates

The full consideration of all these factors is a complex problem that requires detailed modeling of the physical processes (breach characteristics and flood routing), human responses, and the performance of technological systems (such as warning and evacuation systems, transportation systems and buildings under flood loading). This chapter describes a range of practical approaches to this complex problem that can provide life-loss estimates for use in risk analysis.

Consequences Methodologies and Perspectives – USACE and Reclamation

Both the U.S. Army Corps of Engineers (USACE) and the Bureau of Reclamation (Reclamation) perform risk analysis for the dams or levees (USACE only) to assist with risk informed decision making on flood defense infrastructure within each agency's portfolio. While the basic concept of using life loss estimates to help quantify risk is similar between each agencies, the methodologies employed by the two agencies have differences. This consequences estimation chapter is intended for use by both agencies, and is structured in a way that presents general information on life loss estimation, followed by agency-specific subsections.

Life loss estimation models currently in use by USACE include the LifeSim model and HEC-FIA, which contains a simplified version of LifeSim. Importantly, since the simplified LifeSim methodology in HEC-FIA is derived from the LifeSim approach, a specific application of HEC-FIA can be scaled up to a full LifeSim application by developing and gathering the necessary supplemental data.

LifeSim is an agent-based simulation model that tracks the movement of people and their interaction with flooding through time. It includes an integrated transportation algorithm to model the evacuation process, and evaluates loss of life based on location of people when the water arrives and important factors related to building, vehicle, and human stability. Fatalities are estimated by grouping people into one of three “zones”. Each zone has a corresponding fatality rate, which were developed based on an extensive review and analysis of historic flood events.

HEC-FIA includes a simplified version of the LifeSim methodology. Applicability of HEC-FIA depends on the goals of the assessment as well as the characteristics of the study area. The main differences between the simplified LifeSim methodology applied within HEC-FIA and the ful LifeSim methodology include simplifying assumptions related to evacuation simulation and how flood wave arrival times are determined. Grouping of persons into zones and application of fatality rates is similar to the full LifeSim model. More details on the difference between LifeSim and HEC-FIA life loss methodologies are described in the USACE Loss of Life Estimation Methodology section later in this chapter.

Prior to 2014, Reclamation used the DSO-99-06 method for the vast majority of life loss assessments. Beginning in 2014, Reclamation Consequence Estimating Methodology (RCEM) replaced DSO-99-06 as the standard life loss estimating methodology. Both RCEM and DSO-99-06 are based on case history data and judgment. Fatality rates are developed using key parameters including warning time and flood severity. RCEM is relatively simple to apply but requires more judgment than DSO-99-06.

Reclamation has also been developing capability with the Life Safety Model. Similar to the LifeSim model used by USACE, the Life Safety Model is a simulation model that tracks movement of water and movement of people. Fatalities are estimated based on various factors including building destruction, vehicle toppling and drowning. The Life Safety Model has an integrated transportation model, but does not use empirical-based fatality rates.

Summary of Historic Flooding Events

In order to understand the potential for loss of life from flooding and the strengths and weaknesses of the available life loss methodologies, it is important to understand what has lead to loss of life during flood events in the past. All flood disasters are unique in many ways. However, there are a few commonalities that are consistent across most flood scenarios when it comes to how many people lose their life. These common factors include the intensity of the flooding and the time available for warning and evacuation. This section summarizes several historic flood disasters and describes the driving factors that influenced the loss of life for each scenario. Many of these events were used to inform the fatality rates used in LifeSim, FIA, and RCEM. As part of the RCEM, the Dam Failure and Flood Event Case History Compilation includes descriptions of about 60 historical events, with details of the population at risk, flood severity, warning and fatalities.

Teton Dam

Teton Dam, constructed, owned and operated by Reclamation, failed during first filling on Saturday June 5, 1976. The dam was located on the Teton River, about three miles northeast of the town of Newdale, Idaho. Teton Dam was an central-core, zoned embankment dam with a 305 foot structural height (not including 100 feet of additional foundation excavation), and contained 251,700 acre-feet of storage at the time of failure. The cause of failure was internal erosion of the core of the dam, initiated within the foundation key trench.

During the night of June 4, water evidently flowed down the right groin, and a shallow damp channel was noticed early on the morning of June 5. Shortly after 7 a.m. on June 5, muddy water was flowing at about 20 to 30 cubic feet per second from talus on the right abutment. At about 10:30 a.m., a large leak of about 15 cubic feet per second appeared on the face of the embankment, possibly associated with a “loud burst” heard at that time. The new leak increased and appeared to emerge from a “tunnel” about 6 feet in diameter, roughly perpendicular to the dam axis and extending at least 35 feet into the embankment. The tunnel became an erosion gully developing headward up the embankment and curving toward the abutment. At about 11 a.m., a vortex appeared in the reservoir, above the upstream slope of the embankment. At 11:30 a.m., a small sinkhole appeared temporarily, ahead of the gully developing on the downstream slope, near the top of the dam. Shortly thereafter, at 11:57 a.m., the top of the dam collapsed and the reservoir was breached.

Failure of the dam released 240,000 acre-feet in about six hours. Flooding reached the town of Wilford, 8.4 miles downstream, within 30 minutes or so. Six fatalities occurred at Wilford and 120 of 154 homes were swept away. Flooding 12.3 miles downstream at Sugar City arrived at 1:30 pm and was described as a 15 foot high wall of water. At Rexburg, 15.3 miles downstream, flooding arrived at 2:30 pm and reached a depth of 6 to 8 feet within minutes.

Eleven fatalities occurred as a result of the dam’s failure, although it is thought by some that the consequences could have been much worse if the dam had failed at night with no warning. Persons were present at the dam while it was failing and evacuation of downstream population was ordered thirty minutes to an hour prior to the full development of the breach. More than 30,000 people in total were evacuated. Some fatalities occurred when persons who had previously evacuated went back into the flood zone to retrieve possessions.

Out of the eleven fatalities, six died from drowning, three from heart attack, one from accidental shooting and one from self inflicted gunshot wounds.
Maximum dam failure discharge was about 2.3 million ft^3/s at Teton Canyon, 2.5 miles downstream from the dam. At Wilford, the flood is estimated to have attenuated to 1,060,000 ft^3/s.

Figure III-1-1. Teton Dam Failure

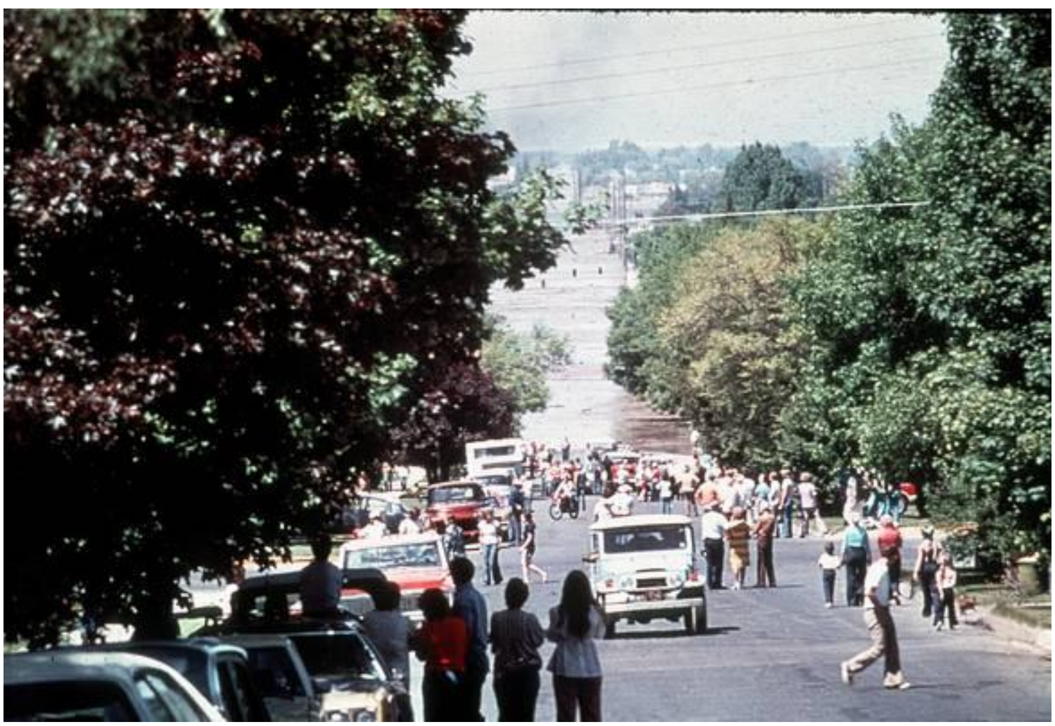

Figure III-1-2. Flooding and evacuation at Rexburg, Idaho

Figure III-1-3. Flood wave propagation across farmland

Figure III-1-4. Flooding aftermath at Rexburg

Summary Table III-1-1. Teton Dam

Warning Time	30 minutes to 1 hour for Wilford, Sugar City and Rexburg
Time of day	Daytime (noon)
Failure scenario	Internal erosion
Fatalities	11
Fatality Rate	0.01 at Wilford, 0.0002 at Rexburg
Dam Height	305 feet
Reservoir Storage	240,000 acre-feet released during breach
Breach Formation Time	1:30
Downstream Distance to PAR	2.5 miles to Teton Canyon, 8.4 miles to Wilford, 15.3 miles to Rexburg
Maximum DV	About 1,600 ft^2/s in Teton Canyon with fast rate of rise, 180 ft^2/s at Sugar City, 30 ft^2/s at Rexburg

St. Francis Dam – Failed in March 1928

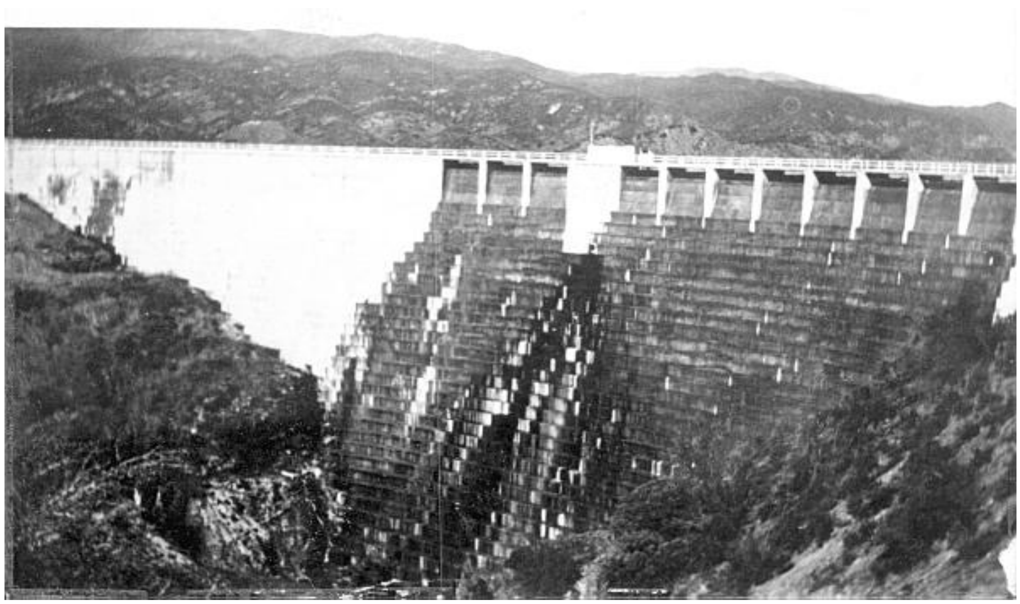

Figure III-1-5 St. Francis Dam Before Failure

St. Francis Dam was located about 37 air miles north-northwest of downtown Los Angeles. The arched concrete gravity dam was constructed to augment the Los Angeles water supply.

St. Francis failed at about midnight, March 12-13, 1928. The flood traveled from the dam, 54 miles to the Pacific Ocean, in a five and one-half hour period during the early morning hours of Tuesday, March 13. The dam was completed in 1926, and was 2 years old when it failed. Failure of this young dam was caused by sliding on weak foliation within the schist comprising the left abutment, suspected of being part of an old landslide.

Figure III-1-6 The Breached St. Francis Dam

St. Francis Dam had a height of 188 feet, and the reservoir volume at the time of failure was about 38,000 acre-feet. The reservoir was about 3 feet below the crest of the parapet at the initiation of dam failure.

The failure sequence for this dam can be considered a worst case scenario. Failure occurred in the middle of the night when many people would have been asleep and darkness prevented people from observing the events that were occurring. The dam failed suddenly with no warning being issued before failure, and the entire contents of the reservoir drained in less than 72 minutes. The dam tender was unable to alert anyone of the danger. He and his family lived in the valley downstream from the dam and perished in the flood.

The Ventura County Sheriff's Office was informed at 1:20 a.m. Telephone operators called local police, highway patrol and phone company customers. Warning was spread by word of mouth, phone, siren and law enforcement in motor vehicles.
Flooding was severe through a 54-mile reach from the dam to the ocean. The leading edge of the flooding moved at about 18 miles per hour near the dam and 6 miles per hour closer to the ocean. There were about 3,000 people at risk and about 420 fatalities, although the number of fatalities reported varies significantly. The fatality rate for the entire reach was about 0.14. It was much higher than this near the dam and much lower as the flood approached the Pacific Ocean. The dam was not rebuilt.

Two downstream areas, Powerhouse No. 2 and Edison Construction Camp, are of particular interest when it comes to understanding how the severity of flooding resulting from this breach lead to relatively high loss of life.

The Powerhouse No. 2 located in the San Francisquito Canyon, about 1.4 miles downstream from the dam. The flood arrived at this location as a wall of water, about five minutes after the dam had failed with an estimated maximum flood depth of 120 feet and peak discharge of 1.3 million ft^3/s. The 60-foot tall concrete powerhouse was "crushed like an eggshell" and the area swept clean. Warning time was zero. Twenty-eight workers and their families lived at the site. There were three survivors.

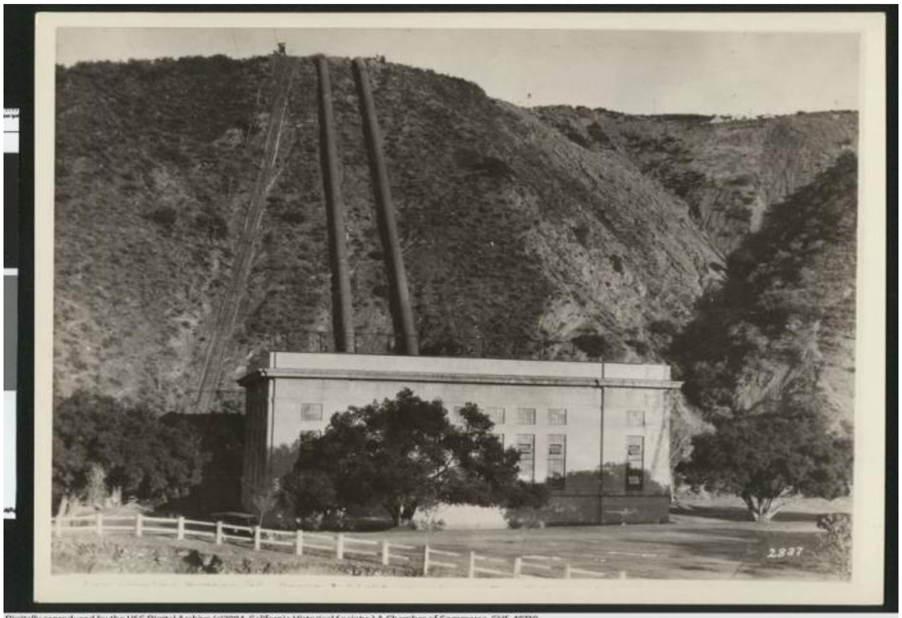

Figure III-1-7 Powerhouse No. 2 before its collapse

Figure III-1-8 Location of Powerhouse No. 2, Area Swept Clean After Flooding

Another area of interest was the Edison Construction Camp located 18.5 miles downstream where 150 men slept in tents along the banks of the river. The flooding at this location was described as a 60-foot wall of water. An effort to issue advance warning to the site was unsuccessful. As the flood approached, a night watchman became alerted and attempted wake the sleeping men, but it was mostly too late. An estimated eighty-four fatalities occurred at this site.

Figure III-1-9 Aftermath of Flooding at the Edison Construction Camp

Farther downstream, at the towns of Fillmore and Santa Paula, there was very intense flooding close to the river channel, but most of the developed areas at these communities were subjected to flooding that was much less severe.

Summary Table III-1-2. St Francis Dam

Warning Time	Zero at Powerhouse No. 2 and the Edison Construction Camp
Time of day	After midnight
Failure scenario	Sudden failure
Fatalities	Unknown at powerhouse No. 2, 84 at Edison Camp, estimate of total flood fatalities ranges from 420 to more than 600
Fatality Rate	> 90% at Powerhouse No.2, 56% at Edison Camp
Dam Height	184 feet?
Reservoir Storage	38,000 acre-feet
Breach Formation Time	instantaneous
Downstream Distance to PAR	1.4 miles to Powerhouse No. 2, 18.6 miles to Edison Camp
Maximum DV	2,960 ft2/s at Powerhouse No. 2

Baldwin Hills Dam – Failed December 14, 1963

Baldwin Hills Dam was an embankment structure that consisted of the main dam and three interconnected dikes, which formed a “ring” that enclosed the reservoir, as shown in Figure III-1-10. The dam which stored municipal water, was located in Los Angeles, California, and was 232 feet high with a crest length of 650 feet. Failure occurred on Saturday December 14, 1963 due to subsidence leading to internal erosion and piping. Baldwin Hills Dam was twelve years old at the time of its failure.

Figure III-1-10. Baldwin Hills Dam

The dam failed at 3:38 pm on a sunny, Saturday afternoon. Seepage from the dam was detected at 11:15 am, and the process of issuing warning was well in advance of the breach. Initially, there was an attempt to draw down the reservoir level and flooding from the releases began affecting residential streets at about 12:20 pm. At 1:45 pm, the decision was made to issue evacuation orders to downstream residents. Neighborhoods were cordoned off and warning was strongly issued via emergency alert broadcasts, helicopters with bullhorns and by policemen going door to door.

Immediately downstream from the dam was a narrow flood channel, approximately 50 to 75 feet wide. Numerous houses were damaged or destroyed in this area, but no fatalities occurred due to a successful evacuation. At about 0.4 miles downstream of the dam was the large apartment complex community known as Village Green. At Village Green, the flow spread laterally east and west, with an approx width of 0.5 miles. All of the five fatalities resulting from the failure of Baldwin Hills Dam occurred in the vicinity of Village Green, including three persons traveling together in a vehicle when overtaken by the flood.

Figure III-1-11. Flooding downstream of Baldwin Hills Dam

A fire department helicopter was responsible for rescuing 18 people caught in the flooding at Village Green. At least six of these persons may have died if they were not rescued.

The pre-evacuation population at risk in the affected area was estimated at 16,500. At least 1,000 people are thought to have remained in the flood zone. Maximum breach discharge was estimated to have been 35,000 to 40,000 ft^3/s. Flooding was reported to have been up to 30 feet deep initially, and maybe 5 to 8 feet deep further downstream with a velocity of 20 miles per hour (29 ft/s).

Summary Table III-1-3. Baldwin Hills Dam

Warning Time	1:50
Time of day	Daytime
Failure scenario	Subsidence leading to internal erosion
Fatalities	5
Fatality Rate	0.0003
Dam Height	232 feet
Reservoir Storage	738 acre-feet
Breach Formation Time	About 4:30 assuming that initial seepage discovered at 11:15 am was the initiation of the breach
Downstream Distance to PAR	Beginning immediately downstream of the dam and extending for three miles when considering the extent of potentially lethal flood flow.
Maximum DV	147 ft^2/s based on an account of 5-foot deep flooding moving at 20 mph. May have been higher in the narrow channel just below the dam.

Damage in the Village Green area was extensive, but many structures remained standing after the flood. The narrow flood channel immediately downstream of the dam experienced high intensity flooding, although no fatalities occurred in this area.

Laurel Run Dam – July 20, 1977

Laurel Run Dam was located on a stream known as Laurel Run located in west-central Pennsylvania, near the town of Johnstown. The earthen dam was 42 feet high with a 623 foot crest length and the reservoir typically held about 300 acre-feet of storage. 450 acre-feet of storage was reported to be in the reservoir at the time of its failure.

Laurel Run had the largest reservoir of seven dams to fail between July 19 and 20, 1977 and caused the most fatalities from this event. The dam is claimed to have failed at 2:35 am on morning of July 20 after a period of heavy rain. 11.82 inches of rain fell in 10 hours, and this was estimated to be between a 5,000 to 10,000 year rainfall event. The dam failed from overtopping. About 41 people were killed in the town of Tanneryville, located in a three-mile long valley, immediately downstream of the dam. Most residents were asleep when the dam failed and no warning was issued. In addition, the rain and night-time conditions limited any escape. Many of the homes in Tanneryville were either damaged or destroyed.

Figure III-1-12 Remains of Laurel Run Dam

Another dam, Sandy Run Dam, was also responsible for several deaths. Overall, there were more than 70 deaths in the area resulting from the effects of this regional flood. The town of Johnstown along the Conemaugh River, famous for the flooding from the 1889 failure of South Fork Dam, was heavily flooded. Damage to Johnstown was extensive, but without fatalities. The area experienced widespread power outages the night of the flood. Telephone service was intermittent in some communities as well. Laurel Run Dam was not rebuilt.

A hydraulic re-creation done by Cheng and Armbruster estimates velocities at the downstream end of laurel Run to have been 24 ft/s. Peak breach discharge was estimated to have been maybe 56,000 ft^3/s. A gage below Laurel Run Dam, at Coopersdale Bridge in Tanneryville, indicated that the flood had attenuated to 37,000 ft^3/s maximum discharge.

Looting was rampant at Johnstown, and the mayor gives the order to “shoot to kill” looters! (not totally relevant but kind of interesting…)
The dam failure flood destroyed many buildings, but the area was not completely swept clean. Maximum breach discharge was estimated by a hydraulic recreation to be about 56,000 ft^3/s, but this flow rapidly attenuated to 37,000 ft^3/s upon reaching Coopersdale. Flood velocity along Laurel Run was estimated to have been about 24 ft/s. Some information is available in a USGS report which cites maximum stage at various locations along Laurel Run, but it is difficult to establish estimates of actual flood depths due to limited ground surface elevation data along the Laurel Run stream.

Summary Table III-1-4. Laurel Run Dam

Warning Time	No warning
Time of day	Dam failure at 2:35 am
Failure scenario	Overtopping
Fatalities	41 from failure of the dam, more than 70 regionally
Fatality Rate	0.27
Dam Height	42 feet
Reservoir Storage	300 acre-feet, 450 acre-feet at time of failure
Breach Formation Time	Unknown
Downstream Distance to PAR	Tanneryville was located along a 3-mile valley between the dam and the Conemaugh River confluence.
Maximum DV	unknown

Figure III-1-13 Laurel Run Dam Location Map

Figure III-1-14 Flooding Aftermath at Tanneryville

New Orleans - Hurricane Katrina, 2005

In 2005, Hurricane Katrina caused one of the worst catastrophes in recent US history resulting in more than 1,100 fatalities in Louisiana alone. The paper "Loss of Life Caused by the Flooding of New Orleans After Hurricane Katrina: Analysis of the Relationship Between Flood Characteristics and Mortality" by Jonkman, Maaskant, Boyd, and Levitan presents an analysis on the loss of life caused by Hurricane Katrina in the city of New Orleans, LA. This section will present some of the ideas and findings of that paper.

Data on the locations, conditions, and characteristics of 771 of the fatalities were available for the study. Of these 771 fatalities that had data associated with them, it was determined that approximately 1/3 of those fatalities either occurred in hospitals or shelters within the flooded area or outside of the flooded area altogether. This meant that 2/3 of these fatalities occurred within the flooded areas and were mostly due to drowning. Due to the warnings that went our prior to Katrina making landfall, it is estimated that 430,000 vehicles had left the metropolitan area using the primary roads. In addition, another 10,000 to 30,000 vehicles left the area by secondary roads. This means an estimated 1.1 million people left the area prior to landfall, which equates to 80% to 90% of the population at risk in the area.

Figure III-1-15. Hurricane Katrina levee failure

The Katrina study looked at age, gender, and race and the role they played in the fatalities. There were 853 fatalities that had some data available for these comparisons. Of most significance was the amount that age factored in to the fatalities. Of the 829 fatalities that the age was known, most were elderly. The report states that less than 1% of these fatalities were children (0-10 years old) and only about 15% were less than 51 years of age. This means that nearly 85% of the fatalities were over the age of 51, 60% were over the age of 65, and almost 50% were older than 75.

The data also showed that gender and race did not play a significant role in the Katrina fatalities. The ratio of fatality rates for men and women were similar to the percentage of men and women that resided in the area before the hurricane. A similar comparison was found for race.

A second study by Jonkman and Kelman researched fatalities for small-scale river flooding in the United States and Europe. Their findings showed that males have a higher mortality rate in those situations. This was attributed to males taking unnecessary risks during those flood events. Their study also showed that the fatality rates for the elderly did not show that they were more at risk. These findings contradict the results for Katrina that show age does have an effect on fatality rate and gender does not. This can be explained by the large-scale and unexpected flooding that took place in New Orleans. During a large-scale event like Katrina, people (males in particular) are less likely to partake in risky behaviors due to the extreme circumstances and survival is more related to endurance in these extreme conditions. This helps explain the high fatality rate for the elderly in New Orleans.

Of the 771 recorded fatalities in the metropolitan area, 624 (81%) were inside the flooded areas and 106 of those were determined not to be a direct impact of the flooding since they were found in hospitals and shelters. The remaining 518 fatalities that were recovered (67% of total recovered) were attributed to direct impact of the flooding (drowning, physical trauma, or building collapse). Of these fatalities, it was determined that many were near large breaches in the levees and therefore, were in areas that experienced deeper water levels.

The highest fatality rates computed in the metropolitan area were in the St. Bernard bowl (Lower 9th Ward), which had rates of 5% to 7%. This is a low lying area that is near two large breaches in the levees. This agrees with past research that shows fatality rates are usually highest near breaches as well as areas that experience deep water levels, fast rising waters, and the collapse of buildings. In the Lower 9th Ward, the two large breaches allowed water to enter the area with great force, causing many buildings to collapse.

Figure III-1-16. Flooding from Hurricane Katrina

The study concluded that fatality rates were highest 1) near breaches due to the combination of depth, velocity, and less reaction time and 2) in areas with the greatest flood depths. One difference between this study and similar studies by Jonkman et al in Europe was that the impact of how quickly the water rose was insignificant in determining the fatality rate. Finally, the study concluded that the fatality rates for Hurricane Katrina were in line with historic events. The overall fatality for this and the historic events analyzed by Jonkman et al is approximately 1% of the population at risk.

Quail Creek Dike - Failed January 1, 1989

Quail Creek Dike, along with Quail Creek Dam, impound the waters of Quail Creek Reservoir, an offstream storage facility located in Washington County, Utah, near the town of St. George. Construction of the dike was completed in 1985. The dike, which was 78 feet high, failed on January 1, 1989 at 12:08 am. About 25,000 acre-feet of water was released from the reservoir which had a capacity of 40,000 acre-feet. Based on eyewitness accounts, the first indication of failure was observed the previous day, although seepage related issues had been a concern for some time. (Quail Creek Failure Report).

Figure III-1-17. View of the breached Quail Creek Dike

The breach released a flood that surged down the Virgin River in waves 10 to 40 ft high, inundating parts of St. George and several other small towns, including Bloomington. Three small bridges were swept away, along with a 98-year-old irrigation dam. The flood also disintegrated half a mile of Utah Route 9, where water thundered through a narrow highway cut adjacent to a bridge about a mile downstream. The surge wiped out utility lines at the crossing, including a newly-completed 8-in. gas line.

Prior to the breach, the Washington County Water Conservancy District, which owns the project, worked for 12 hours to stanch a leak at the toe of the embankment. It initially was spilling 25 gpm. Late in the afternoon of December 31, WCD officials advised the county emergency management director to prepare for downstream evacuations based on unprecedented observations of muddy seepage. The seepage increased to 600 gpm by about 11:00 pm and the dike was breached shortly after midnight. No fatalities occurred. Residents located 15 miles downstream had been warned and evacuated. Late in the afternoon on the December 31, County emergency managers called for downstream evacuations; 1,500 people were evacuated. There were no fatalities.

The 80-foot wide breach was reported to have formed in two hours and released a peak discharge of 60,000 ft^3/s. Flood depths close to the dam were estimated to have been 61 feet high, traveling at 18 ft/s (DV equal to 1,098 ft^2/s). 20,000 acre-feet of storage were drained in five hours. Flooding followed the course of the adjacent Virgin River. Flood flows reached Bloomington, 16 miles downstream, in four hours with five foot flood depths (DV equal to about 29 ft^2/s).

Summary Table III-1-5. Quail Creek Dike

Warning Time	Adequate warning was issued, evacuations were ordered well in advance of the breach
Time of day	Night time
Failure scenario	Static failure, internal erosion
Fatalities	0
Fatality Rate	0
Dam Height	28 feet
Reservoir Storage	40,000 acre-feet
Breach Formation Time	Unknown, but increased seepage leading to the breach occurred for about 12 hours
Downstream Distance to PAR	16 miles
Maximum DV	1,098 ft2/s downstream of dam, 29 ft2/s at Bloomington

General Loss of Life Methodology Overview

Life Loss Estimation: Selecting Scenarios

Failure scenarios for dam safety risk analysis are typically identified from the findings of a Potential Failure Mode analysis. Failure modes usually fall into three categories: static, seismic and hydrologic. Within each category, there may be specific details for a failure mode, such as: overtopping due to a 50,000 year inflow, liquefaction and slumping of a dam crest due to seismic loading or internal erosion due to seepage induced piping along the outlet works conduit. There are many possible, site specific potential failure modes for dams and levees and these are just a few examples. In addition to the basic scenario selection, relevant sub-scenarios can be developed to aid in sensitivity analysis and to estimate ranges of possible outcomes. Life loss estimates based on the evaluation of sub-scenarios can take the form of a highly developed probability distribution, or can be simplified into high, middle and low end estimates.

Depending on the needs of the study, sub-scenarios can be based on:

- Time of day – The time of day affects where people may be located and can affect the ability of PAR to respond to warning and to effectively evacuate. Historically, more fatalities have occurred during night time flood events, due to people sleeping, darkness, decreased ability to spread warning and a slower evacuation response.

- Weekday/Weekend – The day of the week can, in some cases, have an effect on life loss estimates. Recreational areas such as campgrounds, or along rivers where fishing or boating are popular, will see higher PAR numbers on weekends.

- Seasonal variation – For areas with significant recreational (transient) PAR, there may be large differences in numbers of PAR present between summer and winter months.

Additional sub-scenario sensitivity analysis can be performed by evaluating variations in initial reservoir levels for dams or river stage for levees. Variations in breach parameters, such as breach width and breach formation time can also be evaluated as sub-scenarios. Figure III-1-18 shows reservoir levels over a several year period for an example of a dam where initial reservoir sub-scenarios may be valuable. The failure scenario is based on a static condition, or a “sunny day failure”. The failure mechanism is internal erosion. Typically, a sunny day failure will use an initial reservoir level at top of active conservation, or top of joint use if the joint use designation exists for a particular dam. For this example, the dam has a top of joint use elevation of 6769 feet. As can be seen in Figure III-1-18, the reservoir level (in blue) reaches joint use elevation 6769 feet every year, but only stays at that level for a short time. During winter months, the reservoir drops to elevation 6760 feet. Risk analysis sub-scenarios for the sunny day failure condition might include a scenario with the reservoir at top of joint use elevation 6769 feet, and one with the reservoir at an average annual level (in red) of about 6764.5 feet. Note that in practice, an estimation of average annual reservoir level should contain as many years of record as possible. The several years of data depicted in the Figure III-1-18 example is shown only for clarity.

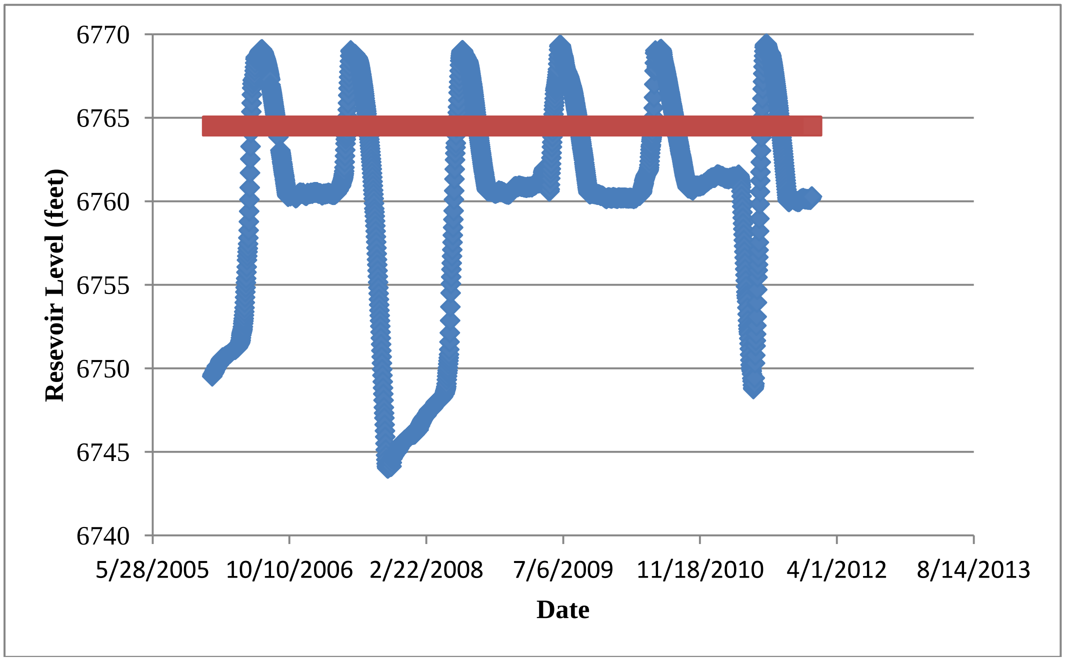

Figure III-1-18. Example reservoir level fluctuation plot

Flood Inundation Modeling

Flood inundation modeling is a critical part of the consequence estimation process. The flood inundation analysis provides estimates of the inundation areas, the intensity (depths and velocities) of flooding, and flood wave travel times.

Inundation analysis should be performed by a specialist who has a broad understanding of hydraulic modeling, dam safety, consequence assessments, and Geographic Information Systems (GIS).

Often, when conducting a risk analysis, an inundation study may exist for a particular dam or levee. An assessment of the existing study should be made to decide whether the study results can adequately represent the scenarios to be evaluated during the risk analysis. The following items should be considered when assessing the adequacy of an existing inundation study:

- Failure scenario - Is the failure scenario portrayed in the existing study comparable to the desired scenarios for the new study? For example, a new inundation study may be justified if the current study seeks to evaluate a sunny day failure with normal reservoir levels, but the existing inundation study is based on a Probable Maximum Flood (PMF) inflow where the inflow volume of the flood increases the breach outflow by 100 percent over sunny day conditions.
- Breach Parameters – Are the breach parameters for the existing study realistic? Are they significantly different from the desired breach parameters of the failure scenario to be evaluated by the risk analysis? An example might be a situation that involves a large concrete gravity-arch dam. The existing inundation assumed failure of the entire dam, all the way to the foundation. Recent finite element structural analysis indicates that the dam, when subjected to the most severe of loading conditions would only breach to the upper one-third of its height. In a situation like this, a new inundation study may be justified.
- Downstream conditions – There are many examples of older inundation studies that were performed with one-dimensional (1D) hydraulic models where the downstream terrain contains populated areas that are very flat. The modeling cross sections may extend over very wide areas, sometimes exceeding several miles in width. The cross sections may even contain vertices or bends in the cross sections which extend uphill in order to artificially create a "lip" in the cross section so that it will hold water. Two-dimensional (2D) hydraulic models do a more accurate job of modeling flood flow over wide flat flood plains, but 2D models did not begin to be used for flood inundation applications until about the late 1990's. For these cases, a new inundation study, using 2D modeling and appropriate terrain data may improve the accuracy in estimating overall flood extent, the intensity of flooding, and travel times and may be warranted (or beneficial).

Figure III-1-19. Example of a 1D inundation study where a 2D study would be most appropriate

One Dimensional (1D) and Two Dimensional (2D) Hydraulic Modeling for Flood Inundation Analysis

Reclamation and USACE make use of different 1D and 2D hydraulic models for flood inundation analysis. These models are described within the agency-specific sections of this chapter. The following discussion contains general information regarding 1D and 2D hydraulic modeling for flood inundation applications.

1D hydraulic models have traditionally been the standard for flood inundation applications. Recently, 2D modeling has become more common practice when the conditions of the study are such that 1D modeling cannot properly capture certain aspects of the flood characteristics. Details of when 1D or 2D modeling should be applied to support consequence estimation are provided below. 1D modeling is the traditional method of utilizing a river centerline to define the flow path, and cross sections to define the channel geometry. An example of a 1D model layout is shown in Figure III-1-20.

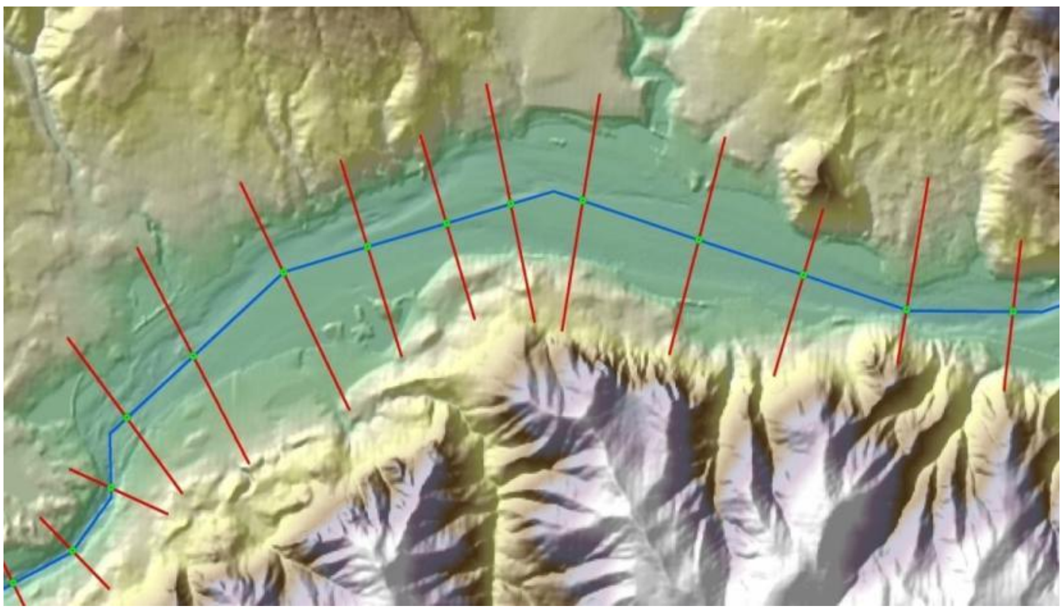

Figure III-1-20. 1D hydraulic model layout. River centerline shown in blue, and cross sections in red

1D modeling is typically applicable in the following situations:

- River systems where dominant flow directions and forces follow the general river flow path (i.e. well defined channels).
- Steep streams that are highly gravity driven and have small overbank areas
- River systems that contain numerous bridges, culvert crossings, weirs, dams and other gated structures, levees, pump stations, etc…. and these structures impact the computed stages and flows within the river system.
- Medium to large systems (50 or more miles long) where the time required for the flood wave to fully propagate through the system is days or weeks. While 2D modeling can be used here, the time required to run 2D models for these situations can be restrictive.
- Areas where the available data does not support the potential gain of using a 2D model. For example, if detailed overbank and channel bathymetry does not exist,

or the only data available includes detailed cross sections at representative locations, many of the benefits of the 2D model will not be realized.

When a 1D model is run, the output is a one-dimensional water surface profile as shown in Figure III-1-21.

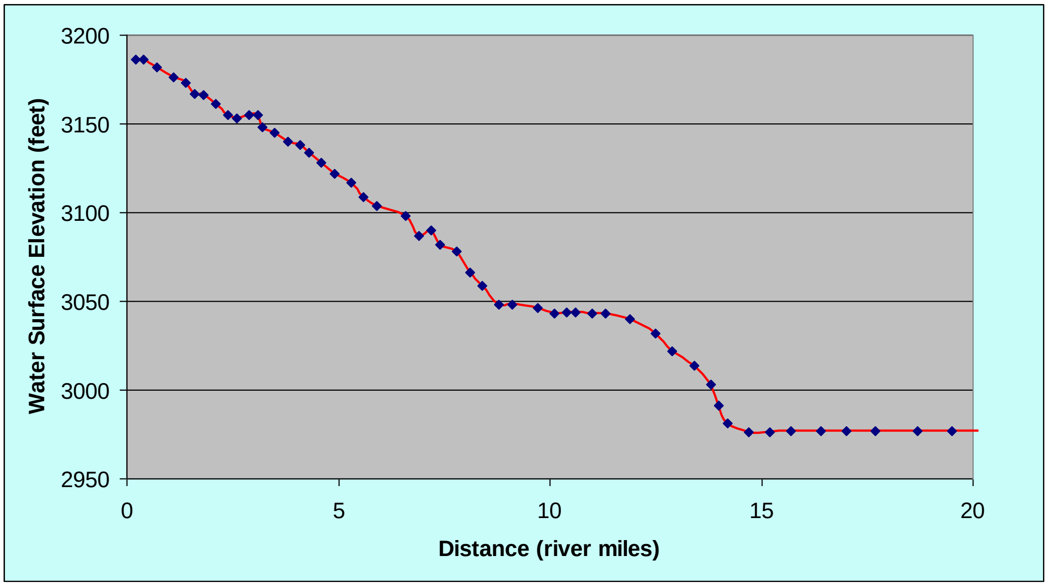

Figure III-1-21. 1D hydraulic model maximum water surface profile output

The 1D model calculates a single water surface elevation for each cross section. In order to create a flood inundation boundary, this 1D result is imposed on a two-dimensional surface. This is accomplished by interpolation. Before the advent of GIS systems, inundation boundaries were hand-drawn on topographic maps, using contour lines to aid in the delineation of the flooding extent. Modern techniques make use of GIS technology. Typically, a Triangular Irregular Network (TIN) methodology is employed to develop the interpolated flood inundation boundary as shown in Figure III-1-22.

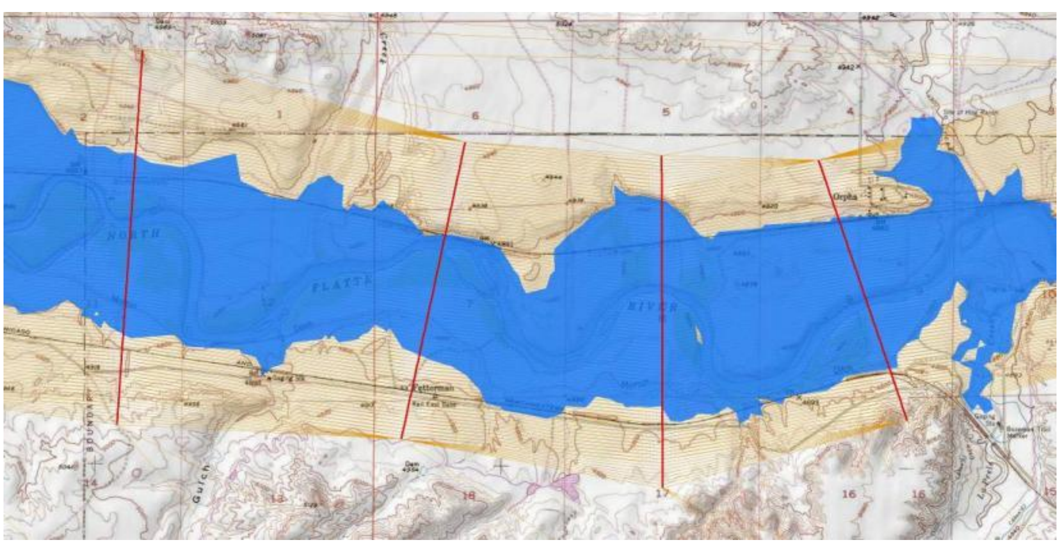

Figure III-1-22. TIN surface and interpolated maximum inundation boundary

Advantages of 1D hydraulic models are:

- Relatively short model run time – typically minutes to hours
- Long reaches are more easily accommodated
- Downstream hydraulic structures such as dams, culverts, bridges can be easily included

1D model disadvantages are:

- Does not provide as much detail or accuracy when considering velocities that are not parallel to the stream centerline
- Does not appropriately handle lateral spreading of flows in very flat flood plains
- Inundation extents are interpolated

2D models have significant differences when compared to 1D models. A 2D model does not use a river centerline or cross sections. Instead, it represents a continuous terrain surface and flow introduced to the model follows the path of least resistance, letting gravity and momentum direct its progression. Every inundated point in a 2D model is a calculated point, so no interpolation is performed. An example of 2D flood inundation modeling is shown in Figure III-1-23.

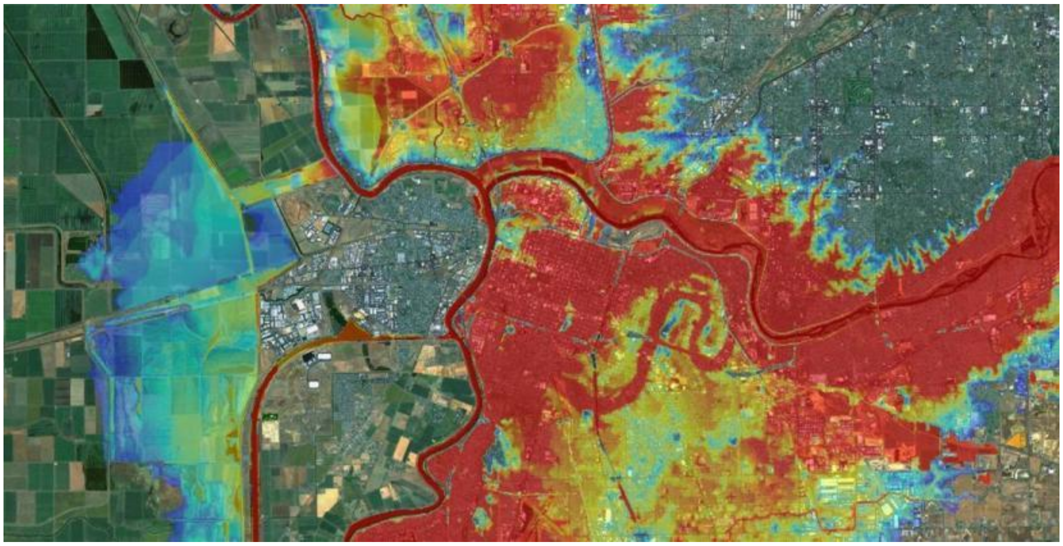

Figure III-1-23. 2D flood inundation example

The inundation depicted in Figure III-1-23 is two-dimensional in that there is a high degree of out of bank flow, lateral spreading and spilt flow. Advantages of 2D hydraulic models:

- 2D modeling works better for areas with flat terrain where lateral spreading of flow is significant (alluvial fans, areas behind levees, etc)
- Complex split flow situations (including highly braided streams) are more accurately handled with a 2D model
- Bays and estuaries where water will flow in multiple directions due to tidal fluctuations and water flows into the bay/estuary at multiple locations and times.
- Flood depths and velocities are computed for every point rather than interpolated between cross-sections. This provides more accurate information in some cases, which can have a significant impact on the consequence assessment.

2D model disadvantages are:

- Relatively long model run times – multiple hours to days or even weeks to run a simulation
- Modeling extent and resolution (size of the model) are restricted by computer hardware limitations – the larger the model, the longer it takes to run a simulation, and it can be difficult to run long river reaches at a reasonable terrain resolution
- Model simulation time is also restricted by computer hardware limitations – this is particularly true for hydrologic scenarios where spillway releases from a dam occur for a long period of time prior to the initiation of a dam breach.

Note that highly detailed inundation modeling may not be justified when the estimation of life loss consequences involves lightly populated areas.

Breach Parameters

The selection of breach parameters for dams and levees can be an extremely important consideration for consequence assessments. The breach parameters can affect the peak breach discharge and the timing of the downstream flood arrival in a very significant way.

1D numeric hydraulic models are typically utilized to develop breach outflow. There are two breach mechanisms that are commonly used, piping and overtopping. The piping breach formulation involves a hole in the embankment, which releases flow and gradually becomes wider, eventually collapsing into a trapezoidal or rectangular shaped breach. The overtopping breach formulation assumes that the breach is either trapezoidal or rectangular, and that it forms from the crest of the structure downward, towards the foundation.

The selection of breach parameters should be appropriate to the desired failure scenario. For embankment dams, the width of a breach should account for the size of a reservoir and the material properties. For example, the breach of a large volume reservoir may mean a longer time for the reservoir to drain and this increases the chances for lateral erosion. which will create a wider breach. At the same time, embankment material that is erosion resistant may reduce the widening effect.

Historically, the failures of concrete dams have been observed to occur suddenly and catastrophically. Examples of this are St. Francis Dam and Malpasset Dam.
There are several approaches that can be used to estimate breach parameters. Empirical formulations, based on dam failure case histories, have been widely applied to the estimation of dam and levee breach analysis. The Reclamation report: Prediction of Embankment Dam Breach Parameters, A Literature Review and Needs Assessment, DSO-99-04, provides a summarization and analysis of commonly used empirical breach parameter formulations. An excerpt of DSO-99-04 which briefly describes some commonly used empirical breach formulations is shown in Figure III-124. It is important to understand the range of case studies that the empirical equations are derived from before applying them to a given dam.

Reference	Number of Case Studies	Relations Proposed (S.I. units, meters, m^3/s, hours)
Johnson and Illes (1976)		$0.5h_d \le B \le 3h_d$ for earthfill dams
Singh and Snorrason (1982, 1984)	20	$2h_d \le B \le 5h_d$ $0.15\ \text{m} \le d_{ovtop} \le 0.61\ \text{m}$ $0.25\ \text{hr} \le t_f \le 1.0\ \text{hr}$
MacDonald and Langridge-Monopolis (1984)	42	Earthfill dams: $V_{er} = 0.0261(V_{out} * h_w)^{0.769}$ [best-fit] $t_f = 0.0179(V_{er})^{0.364}$ [upper envelope] Non-earthfill dams: $V_{er} = 0.00348(V_{out} * h_w)^{0.852}$ [best fit]
FERC (1987)		B is normally 2-4 times h_d B can range from 1-5 times h_d Z = 0.25 to 1.0 [engineered, compacted dams] Z = 1 to 2 [non-engineered, slag or refuse dams] t_f = 0.1-1 hours [engineered, compacted earth dam] t_f = 0.1-0.5 hours [non-engineered, poorly compacted]
Froehlich (1987)	43	$\overline{B}^* = 0.47K_o\left(S^*\right)^{0.25}$ K_o = 1.4 overtopping; 1.0 otherwise $Z = 0.75K_c(h_w^*)^{1.57}(\overline{W}^*)^{0.73}$ K_c = 0.6 with corewall; 1.0 without a corewall $t_f^* = 79(S^*)^{0.47}$
Reclamation (1988)		$B = (3)h_w$ $t_f = (0.011)B$
Singh and Scarlatos (1988)	52	Breach geometry and time of failure tendencies B_{top}/B_{bottom} averages 1.29
Von Thun and Gillette (1990)	57	B, Z, t_f guidance (see discussion)
Dewey and Gillette (1993)	57	Breach initiation model; B, Z, t_f guidance
Froehlich (1995b)	63	$\overline{B} = 0.1803K_oV_w^{0.32}h_b^{0.19}$ $t_f = 0.00254V_w^{0.53}h_b^{(-0.90)}$ K_o= 1.4 for overtopping; 1.0 otherwise

Figure III-1-24. Empirical breach formulations from DSO-99-04

Recent developments have occurred in the area of physical breach parameters for overtopping of homogeneous embankment structures. The WINDAM B program has been designed by the Agricultural Research Service (ARS) and the Natural Resources Conservation Service (NRCS), and is part of a larger effort conducted by the CEATI International, Dam Safety Interest Group to develop physical breach parameter modeling tools. WinDAM B models erosion in earthen embankments as well as erosion in earthen auxiliary spillways of dams. The three-phase erosion model uses threshold-rate relationships based on the process mechanics. A headcut erodibility index (K_h) describes the resistance of the exposed geologic materials to erosive attack during the third phase of the process. Preferred input data for the WINDAM B would come from on-site, in situ testing of embankments. However, approximations of detachment rate coefficients and critical shear stress can be made. These approximations are be made based on percent clay, compaction rate and moisture content values, if these values can be obtained. Another method of estimating breach parameters is what could be referred to as a site specific, knowledge-based estimate.

Many of the dams in the USACE and Reclamation inventories have been extensively studied, analyzed and monitored. Potential failure modes have been developed, multiple inspections have been performed, details of design and construction have been compiled and the mechanics of failure modes have been analyzed. As a result of all of this, much is known about the dam and senior engineers assigned to a given dam may have opinions on how the failure might occur. Consultation by inundation modeling analyst with senior engineers assigned to a particular dam or levee may aid in the development of site specific breach parameters, based on what is knowledge of the dam, its composition, performance and its response in regards to potential failure modes. This approach may include the analysis of empirical breach equations, but in many cases is just based on informed opinions about the specific dam in question. There are a lot of uncertainties in the prediction of breach parameters and this approach can be valuable in that it enables collaboration and helps to build consensus between the inundation/consequences analyst and those who will be using the study results for risk analysis.

Inundation Modeling Terrain Data

Terrain data for inundation modeling is important. Current hydraulic models rely on GIS for pre- and -post processing. Digital elevation models (DEM) have become the most commonly used terrain data format. The DEM is a raster or grid based format, similar to a matrix of equal sided cells containing a single elevation value. Some hydraulic models make use of terrain data in a TIN surface format rather than a DEM format. Certain 2D hydraulic models require the creation of what is called an unstructured mesh, which is a network of various sized triangles or trapezoids. Surveyed cross section data are sometimes used as well. In general though, there are several common types of digital terrain data sources:

- USGS DEMs – USGS produces DEMs which can be downloaded for free from the National Elevation Dataset (NED) website, ned.usgs.gov NED DEM data is usually available in 10 and 30-meter resolution. This is for the most part, lower resolution terrain. However, the NED DEM data is widely used and can be of adequate quality and resolution for modeling high discharge dam breach flows downstream of large storage reservoirs.

- IFSAR Terrain data – Interferometric Synthetic Aperture Radar (IFSAR) data is radar-based terrain data which is collected from the wing of an aircraft. IFSAR data is processed to remove vegetation, man made structures and other features to produce a "bare earth surface". The currently available data is "medium quality resolution", significantly better than the USGS NED data. IFSAR data has 1-meter accuracy, both vertical and horizontal. Intermap Technologies, www.intermap.com, has collected IFSAR terrain data for the entire 48 U.S. mainland states. This data is readily available and pricing of the data is very reasonable in comparison to higher resolution options. IFSAR data can be a good option when USGS NED data does not contain enough information to accurately portray downstream features. This would be particularly true when modeling lower discharge dam breach or levee breach flow and/or where flat terrain in downstream areas does not contain enough detail in the USGS NED data to have confidence in the modeling results.

- Aerial Photogrammetry – Interpretation of aerial photography can produce digital terrain data with a variety of accuracy that depends on photo scale (flying height). This data can be very good quality, although it can be expensive and time consuming to acquire. Photogrammetric data may have cost advantages over LIDAR when detailed data is desired within a small area.

- LIDAR - Light detection and ranging data (LIDAR) is laser-based data that is flown from an aircraft, much like the IFSAR data, but at a higher accuracy. LIDAR data typically has a vertical accuracy of +/- 15 cm (about 6-inches).

The “bare earth surface” produced by LIDAR data is typically of very high accuracy. LIDAR is expensive and time consuming to acquire, but when the highest resolution data is needed, LIDAR may be the way to go. Note that ground-based LIDAR systems also exist and may be of value to collect detailed data within a small area of interest.

Using the power of a GIS, a wide variety of data formats can be utilized if available. For example, vector contour line data can be converted to DEM format, point data can be converted to TIN, TIN can be converted to DEM, etc. GIS technology allows the integration of a wide variety of potential data sources.

Note that higher resolution data such as photogrammetric or LIDAR may have been acquired by local entities who may be willing to share the data at low or no cost. There is often value in contacting local county or city GIS offices to inquire about the existence of such data.

In working with different terrain types, it is important to keep a perspective on terrain accuracy versus terrain resolution. For example, changing the resolution (known as re-sampling) of a USGS NED 10-meter DEM from 10-meters to 3-meters does not make the data more accurate. However, re-sampling LIDAR data to a 10-meter resolution will provide more accurate data than the 10-meter NED DEM, since the vertical accuracy of the NED data is much lower than the LIDAR data. There are limits to this; re-sampling LIDAR data to a 1,000 or even 100-meter resolution, for the purpose of creating faster 2D model run times loses all the benefits of vertical accuracy that were gained with the LIDAR data.

The modeling of dam failure scenarios which include the operation and/or breaching of downstream dams may require the development of downstream reservoir bathymetry in order to properly represent the dam and reservoir in the model.

Inundation Modeling Outputs

Inundation modeling outputs are used to develop a variety of information that is useful for estimating life loss. A standard inundation modeling output is the maximum inundation polygon. This is the flood boundary that is typically shown on an inundation map. The maximum inundation polygon depicts the widest and most severe extent of flooding that occurs in all of the downstream areas. In reality when upstream areas become inundated, the downstream areas have not yet been flooded. When these downstream areas reach maximum flooding, the upstream areas might start to dry out. The maximum inundation polygon is useful for viewing the maximum flooding that may occur at all flooded locations throughout the duration of the flooding event.
In additional to maximum inundation, typical inundation modeling output data includes flood depths, velocities, water surface elevations, maximum discharge, arrival time of leading edge and arrival time of maximum flooding.

1D models traditionally have presented output data at cross section locations. This data is typically portrayed in a tabular format. On an inundation map, it is common to depict cross sections, labeled by their location. A Table on the map will include output information referenced to the cross sections.

2D models do not have cross sections and the presentation of 2D modeling results may make use of a variety of formats. 2D inundation polygons can be color-coded according to ranges of depth, velocity or DV. In addition to the maximum inundation polygon, it is easy to display "snapshots in time" which depict the entire flood configuration at a particular time of interest, for example - three hours after the initiation of the breach. The leading edge of flooding is irregular and a poly line data set can be digitized in the GIS to represent the front edge of the flood at various time steps. Maximum discharge and time to maximum flooding information can be obtained by extracting hydrographs from the 2D model output data at areas of interest. Interpolated results from 1D modeling output can be presented in a format similar to what is done with 2D modeling output. Care must be taken though when presenting 1D results in this manner, not to misrepresent the accuracy of the study in question.

Estimation of Downstream Population at Risk

Life loss estimates are based on some assumption of the number of people that are present in the flood zone. There are different life loss estimation methods that take various approaches to how they develop fatality estimates, but one thing these methods all have in common is that they require an initial estimate of PAR. At a very basic level, the development of a PAR estimate can be as simple as visiting a site below a dam or levee and counting houses in the inundation zone. One of the online map services such as Google Maps, Google Earth or MapQuest can also be used to count inundated houses. Typically, PAR is estimated using the U.S. Census data. Often, PAR estimates are based on residential PAR. The most accurate data for residential PAR estimation is at the level of the census block. The flood inundation boundary can be overlaid with the census block data in a GIS, and the number of inundated PAR households can be calculated. Partially inundated census blocks must be treated separately. If the residences are evenly distributed within the partially inundated block, a percent inundated estimate can be applied to the total number of households within that block. If the distribution of residences within a partially inundated block is more concentrated in specific locations, then an approach would be to manually count the houses in the inundation zone. Finally, the total number of inundated residences is multiplied by an average household size that is specific to the area of interest, to obtain the estimated residential PAR.

Figure III-1-25. Census block/inundation overlay

The use of residential PAR for life loss estimation is a simplifying assumption. If more detailed information is known about where people may be located during daytime hours, then this information can be used to develop daytime-specific life loss scenarios. Care must be taken though, not to double count PAR when looking at non-residential PAR distributions. A good example of this is a Reclamation Dam that has a mill operation located immediately downstream. The mill has maybe 400 employees present during daytime hours. The proximity of the dam to these employees puts them at the highest level of risk in the event of dam failure. It is unknown however, where the residences of these employees are located. Some may live in the flood zone at locations further downstream, and because of this they may be double counted. In this case though, the fatalities close to the dam can be assumed to be high and persons living downstream in the floodplain are assumed to have much more time to evacuate, so that the issue of potentially double counting is not considered to be introducing major errors. Double counting of PAR when considering non-residential situations should be evaluated on a case by case basis to avoid the possibility of overestimating fatalities.

Another type of PAR that is frequently estimated is recreational or transient PAR. This would include persons occupying campgrounds, fishing, boating or hiking along a river, etc. Recreational PAR estimates can be obtained through site visits and/or by consulting with land use and recreation management groups who oversee these areas. In some cases, visitation numbers data may be available, or in other cases, campground hosts or park rangers may have a general idea of user numbers. Typically, recreational PAR will vary by time of year and day of week, with great numbers in the summer months and on weekends. Day use areas will of course have higher PAR during daytime hours, with low or no PAR present during the evening.

Warning and Evacuation

In the most ideal situation, a dam breach in progress would be detected well in advance of the beginning of catastrophic outflows, clear evacuation orders would issued to downstream PAR without delay, and all of the PAR would move safely out of the flood zone by the time flooding arrives in their area. Unfortunately, dam failure and flash flood case histories have shown that things don't always go that smoothly. The sequence of events that takes place is often a mix of physical and social phenomena, sometimes combined with a dose of luck or chance.

The issuance of warning and the decision of downstream PAR are critical factors that impact the potential for life loss. Past dambreak flood instances show that, in general, the number of fatalities decreases as the distance downstream increases, but increasing distance by itself is not what decreases the life loss potential. Potential life loss decreases when the travel time begins to exceed the amount of time required to warn and evacuate the population at risk. A combination of breach development rate and flood wave velocity determines the flood wave arrival time for a given distance. Then, the distance to a safe haven, the escape route capacity, and various human perceptions and choices determines who might be caught within inundation boundaries when the flood arrives.

Another attribute of increasing distance is the attenuation (reduction) in flow that occurs. However, flow depths and velocities can increase downstream if the flood plain transitions from a wider valley to a narrow canyon.

Warning time is broken into stages: detection of the threat, decision to issue warning, notification of the downstream PAR, and warning dissemination. Detection of a developing dam failure situation could be by automated instrumentation, by visual inspection by project personnel or by someone passing by the area such as a hiker or fisherman. After the unusual situation is noticed, some time is required before project and emergency preparedness personnel assess the situation and decide that there is a reasonable chance it will develop into a condition that cannot be controlled. Then, the notification of those responsible for spreading the warning can take some time. The actual warning to the population at risk can be transmitted many ways, each with its own degree of effectiveness. The content and wording of the warning message is very important when it comes to how quickly people will take the necessary precautions, either giving people a strong perception of the danger or not. Warning can also spread by word-of-mouth through friends, family, neighbors, and concerned citizens. People who are at risk, but are not warned verbally, can still perceive danger by hearing an unusual sound or seeing a rapidly rising flow.

Estimation of the warning and evacuation process may include consideration of the following issues:

- Failure of the dam or its impending failure may need to be verified before warning is issued.
- The decision to order evacuations must be made. Often the decision makers will weigh the evidence at hand regarding the likelihood of catastrophic flooding vs. perceived issues of public distrust when determining whether to issue a warning.
- After a warning is issued, it will spread through the targeted community. The speed at which is spreads is based on the types of warning systems/channels employed by the agency issuing the warning. There is no silver bullet when it comes to the best, most effective warning system. Research shows that using a wide range of traditional and recent technology provides the most efficient warning dissemination.
- People may receive warning or an order to evacuate, but may delay taking a protective action (e.g. evacuation) or may choose not to leave at all. The timeliness of taking the recommended protective action is heavily influenced based on the content of the warning message. Clear messages that contain information about the threat, the source of the warning, the potential consequences, specific instructions on when to leave and where to go are much more likely to lead to a quick response than those lacking information.
- Persons who do not attempt to evacuate or who attempt to evacuate at the last minute can be placed in critical situations where a number of factors may influence their survival. The flood depths, the intensity of flooding (often quantified as a function of depth and velocity), the strength of a shelter, and a person's physical condition will influence the survival chances of PAR exposed to flooding.
- Some people may not evacuate. Reasons for this include: warnings may not be taken seriously; elderly persons or disabled persons may have too much difficulty attempting to evacuate; people may not evacuate for fear of looting; people may not believe that the flood impacts will be severe enough to endanger them; people delay evacuation to protect personal property such as pets or livestock.
- Densely populated urbanized areas need more time to evacuate. These are special situations where traffic congestion may play a role in the ability to evacuate. Persons attempting to evacuate in advance of flooding may get stuck in traffic,

resulting in exposure to flooding. In many situations, evacuating to a large, sturdy building, or staying in one's home may be safer than attempting to leave the area in a vehicle. Note that life loss simulation models such as LifeSim and Life Safety Model use transportation network models and attempt to address traffic congestion issues during flood events.

Case history data provides some examples of human behavior in relation to flood risk and evacuation:

- The failure of the Macchu II Dam in India in 1979 killed as many as 25,000 people. Once warned, some people didn't leave because they lived above the highest flood levels that had occurred during their lifetime.
- Teton Dam failure in 1976 (11 fatalities) and Lawn Lake Dam failure in 1982 (3 fatalities) both contained fatality incidents where people who had safely evacuated re-entered the flood zone to retrieve possessions, thinking that they had more time before the arrival of flooding.
- The eruption of the Nevado del Ruis volcano and the deadly lahar mudflow flood at Armero, Columbia in 1986 killed about 22,000 people. Most residents of Armero didn't evacuate because the severity of risk was downplayed by local officials.
- St. Francis Dam failed in 1928, killing more than 400 people. Some who heard the approaching flood waters could not conceive of a dam failure flood and thought the sounds to be due to a windstorm.

Experience indicates that there is sometimes a reluctance to issue dam failure warnings. The operating procedures or emergency actions plan that may be available for a dam or levee should provide some guidance regarding when a warning would be issued. There is no assurance, however, that a warning would be initiated as directed in a plan. A study investigating loss of life from dam failure can be used to highlight weaknesses in the dam failure warning process and provide some guidance on how improvements in the process would reduce the loss of life. Sensitivity analysis should be used to provide information on how significant warning issuance is to the uncertainty in a life-loss estimate.
For most breach mechanisms where the breach progression is observable prior to catastrophic failure of the dam or levee, the time when a warning is issued should be determined by first estimating the time when a major problem would be acknowledged relative to the time of dam failure. The major problem acknowledgment time for these failure modes is the time when a dam owner would determine that a failure is likely imminent and they would decide that the dam breach warning and evacuation process should be initiated by notifying the responsible authorities. The time lag between major problem acknowledgement and when an evacuation order would pass from the dam owner to the responsible emergency agency (EMA) and then from the EMA to the public should be estimated based on available research, judgment of consequence specialists familiar with that research, dam operations personnel and emergency management personnel who have jurisdiction in the areas of each downstream community.

The amount of time it takes from when the evacuation warning is issued by the responsible agency (warning issuance) until the population at risk receives that warning is dependent on the number and type of warning systems or processes that are used to disseminate that warning. A typical warning would be received by the population through various means. For example, the first group of people would typically receive warning through the primary warning process (e.g. Emergency Alert System), but then a secondary warning process would begin that includes emergency responders and the general population spreading that warning via word of mouth.

Intensity of Flooding and Fatality Rate

Fatality rates represent the percentage of people exposed to flooding (typically known as threatened population) that lose their life. An important difference between RCEM and the simulation models used by USACE and Reclamation is that RCEM defines fatality rates as the percentage of pre-evacuation PAR that loses their life rather than a percentage of exposed exposed to the flooding (those remaining after evacuation has taken place). In either case, fatality rates are typically derived from empirical data.

The intensity of flooding can be correlated to the potential for fatalities. This intensity is often quantified in terms of depth multiplied by velocity, or DV. Mapping of DV can be produced from 1D or 2D modeling results and the DV maximum inundation boundary can be overlaid with census data in a GIS to assess zones of various levels of destructive intensity (also referred to as flood severity). Note that 2D hydraulic modeling can provide greater accuracy when assessing lateral variation of DV. Flooding depths are an important measure of flood intensity as well. Deeper water can make evacuation on foot impossible, submerge roads, float cars and mobile homes, and make structures uninhabitable. Fatality rates can be influenced by both flood depths and DV.
The potential for collapse of buildings within the flood zone can be some measure of the potential for fatalities, assuming people are present when the flood arrives. Most residential buildings would be vulnerable to major damage and/or collapse when flooding DV exceeds the range of 7 to 15 m^2/s.

Modeling assumptions that affect fatality rates can be adjusted when justified by extenuating circumstances. If a particularly devastating earthquake is responsible for dam failure, it is possible the earthquake has also devastated infrastructure and communications in population centers in the vicinity. Every aspect of warning (i.e. detection, decision, notification, and dissemination) may be affected, and evacuation routes may be compromised. Emergency management personnel would be responding to several situations and will not be able to devote their entire attention on a developing situation at a dam. Using RCEM, it may be reasonable to increase the fatality rates for this case. For the simulation-based approaches, these considerations would be handled explicitly by adjusting the parameters in the warning and evacuation modeling.

Regardless of the life loss prediction method that is used, there is a great deal of uncertainty in all aspects of the life loss estimate. Therefore, communicating risk to decision-makers should be as a range, or better yet, as a graphical depiction of likelihood. The general shape of likelihood distribution graphs can be envisioned by thinking through many hypothetical scenarios. For example, many Reclamation dams have few people living within the dam break flood inundation boundaries, and many failure scenarios can be envisioned taking place very slowly with a long warning period. In these situations, it would make sense that there would be a significant likelihood of zero life loss. One could envision many dam break scenarios for the same dam and population, starting at different times of the day, breaching with different rates, and given various warning and evacuation scenarios. If many of these scenarios would end in life loss, there might be a range between zero and some number where the estimate is likely to fall. One could also envision some small chance that everything could go wrong, and that in these rare instances, a large number of lives would be lost. A fatality likelihood distribution could look like Figure III-1-26.

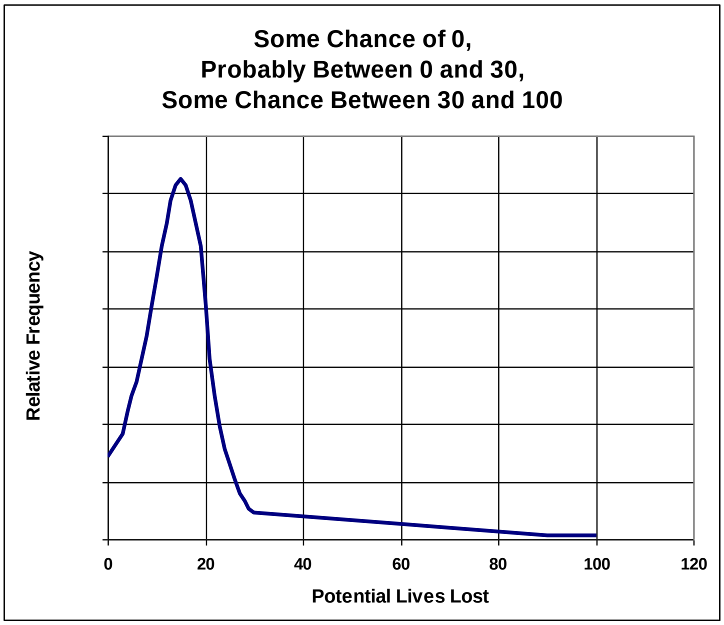

Figure III-1-26. PDF Example Fatality Distribution for Small Population at Risk

Another example might occur when the population at risk is much larger, and the dam is expected to fail much more quickly. In this case, it is much less likely that there would be zero life loss. But again, the expected life loss envisioning many different scenarios would likely fall in a range, with a tail of less-likely estimates to represent the extreme values. This distribution would look like Figure III-1-27.

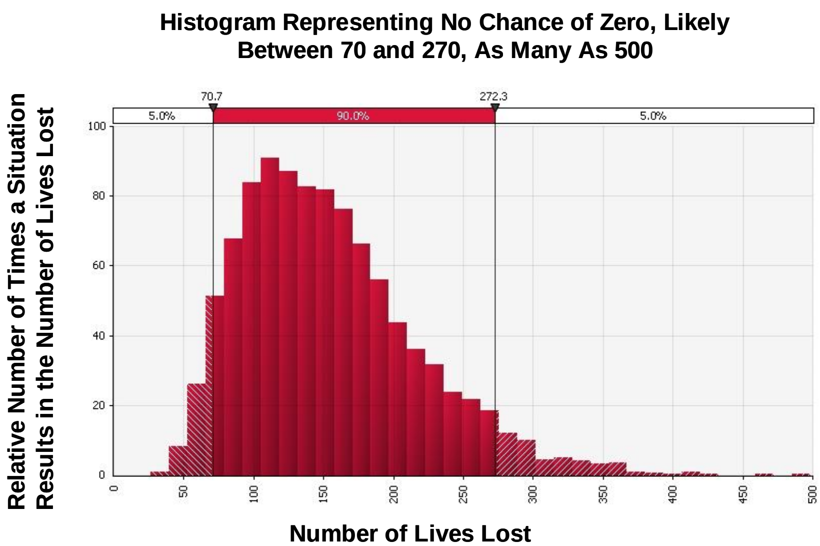

Figure III-1-27. Histogram Example Fatality Distribution for Rapid Failure with Large Population at Risk

Reclamation Consequence Estimating Methodology (RCEM)

Since September 1999, life loss from assumed failure of a Reclamation dam has been estimated using the published document "A Procedure for Estimating Loss of Life Caused by Dam Failure," or report DSO-99-06. RCEM is very similar to the DSO-99-06 approach. DSO-99-06 provided suggested fatality rates to be applied to downstream populations subjected to dam breach flows, considering the warning time, flood severity, and flood severity understanding. RCEM involves consideration of these same elements as well as other factors when selecting a fatality rate for a given exposed population, and features a graphical presentation of fatality rates versus warning time and flood severity. DSO-99-06 was based on the analysis of dam failures, flash floods and other floods located primarily in the United States. Additional case histories were investigated for RCEM and added to the database that forms the basis for the empirical approach. The new database of flooding case histories has been expanded by more than 50 percent.

For the past 15 years, Reclamation has preferred an empirical approach to estimating life loss; one based on interpretation of dam failure and flood case histories. RCEM continues to rely on case history data to guide the selection of fatality rates. There is a large uncertainty inherent in the estimation of life loss resulting from dam failure, in part due to large possible variations in the development and progression of breach flows, as well as numerous potential ways that the downstream public receives warning (if any) and the manner in which they respond to warning. The study of flooding case histories reinforces the finding that there are a wide range of possible outcomes from dam failure, ranging from no fatalities to thousands of lives lost. The use of such empirical findings and the resulting procedure based on these data are intended to reflect the variability associated with life loss, as well as encourage the use of judgment in considering the many variables associated with estimating life loss. Lessons learned from the case histories show that a wide range of fatality rates are possible, and thus a range of life loss should be portrayed rather than single point values.

Inundation Modeling at Reclamation

Reclamation's inundation modeling work makes use of the Danish Hydraulic Institute (DHI) MIKE models. MIKE11 is used for 1D modeling, and MIKE21 for 2D. These two models can be linked or "coupled" using a utility known as MIKEFlood.

MIKE11 contains the National Weather Service DAMBRK breach formulation which can be used for both piping and overtopping breach analysis. The MIKE11 model also contains other structure routines for spillways, outlets, culverts, weirs and bridges. Multi-dam breach analysis can be performed and logical operating conditions, useful for modeling multi-dam scenarios, can be implemented. MIKE11 is linked to ArcGIS through Model Interface One (MIO). MIO is a Reclamation developed interface to ArcGIS for MIKE11 that allows pre- and post processing. MIKE11 river network alignment and cross sections can be extracted from data in ArcGIS and directly imported to a MIKE11 input file. 1D modeling results are then exported back into ArcGIS to create an interpolated maximum inundation boundary using TIN methodology. MIO also allows the interpolated TIN surface to be modified for various reasons such as addressing inundation at tributaries and cutting off upstream TIN influences which may artificially increase the extent o downstream inundation.

MIKE21 uses a structured mesh which allows direct import of DEM data from ArcGIS as input terrain data. MIKE21 outputs are also easily exported back to ArcGIS for post-modeling analysis. Hydraulic structures from MIKE11 can be linked to MIKE21 via MIKEFlood. Terrain data can be modified to include features such as downstream river levees or canal embankments using ArcGIS.

RCEM

The Relationship between Flood Severity and Fatality Rate

The graphical approach to estimating the fatality rate utilized in RCEM is very similar to the tabular approach described in DSO-99-06, which provides recommended ranges based on case history data. However, the graphical approach involves greater consideration of the case history database for making judgments about fatality rates.

Analysis of the case histories indicates that flood severity (a measure of the lethality of the flood) and warning time are the factors that most influence the fatality rate for a flood. The paragraphs that follow discuss the basis for establishing a relationship between flood severity and fatality rate as the foundation for the graphical approach. This relationship was established by studying the case history database and extracting what was judged to be the best available information.

Flood severity, as developed within DSO-99-06, consists of low, medium, and high severity flooding. RCEM goes beyond this category assignment and relies more on assessing the flood severity as estimated by depth multiplied by velocity (DV). Flood severity has a significant influence on fatality rate. Case history data indicate that the highest observed fatality rates are associated with the highest estimated DV values. When the flood severity is lower, there is a general trend of lower (or no) fatalities; however, there is greater scatter in the fatality rates for lower flood severity values. In developing RCEM, the numerical measure of flood severity, DV, was estimated for each case history event using available documentation and engineering judgment. The confidence level in the estimated DV varied depending on the amount and quality of the available information.

The fatality rates are applied to the full population at risk, and do not explicitly consider evacuation of downstream populations. The likely success of evacuations is something that can be considered when selecting ranges for fatality rates using the RCEM methodology. It is recognized that evacuation has a significant influence on the number of fatalities from a flood. Obviously, for cases where the maximum number of people was evacuated, the fatality rate with respect to the original PAR was lower – independent of the DV value. However, the case history data do not provide a meaningful way to extract PAR evacuation information such that a relationship involving evacuation as a primary parameter can be established. Therefore, for the graphical approach, evacuation is considered implicitly through the parameter of warning time – i.e., greater warning time results in lower fatality rates because a greater portion of the PAR is able to evacuate the flood area.

The amount of warning received by a PAR is typically part of the case history documentation. For the same event, there may be several different population groups, and each may have received a different amount of warning time. A review of the case history data indicates that in most cases, the PAR received either little to no warning, or hours of warning. The way that "some" warning was defined in DSO-99-06 is as a relatively narrow window of time (between 15 and 60 minutes), and thus most cases have warning times that tend to fall outside of these limits. For many of the older case histories (i.e. prior to about the mid-1900s) communication networks and emergency management systems were not in place to enable warning. In addition, there may have been a general reluctance to issue a warning too soon, with operating personnel instead waiting until failure was more certain or there may have been a lack of understanding that dam overtopping could lead to dam failure. For these reasons, with older case histories, receiving hours of warning was rare.

Given the above considerations, the basis or foundation for the graphical approach involves establishing continuous relationships between flood severity and fatality rate for different warning time scenarios. Because of the relative lack of case histories with "some" warning time, only two warning time scenarios, little to no warning and adequate warning, are used in RCEM. These terms are not tied to a specific amount of warning; that is left to the judgment of those making the life loss estimates.

Graphical Approach – Suggested and Overall Limits

Two charts were developed for selecting fatality rates using the graphical approach; Fatality Rate vs. DV for Little or No Warning (Figure III-1-28), and Fatality Rate vs. DV for Adequate Warning (Figure III-1-29).

Each chart includes dashed lines that represent "suggested" and "overall" limits for fatality rates over the full range of DV values. The suggested limits were selected based on the most representative case history data points for each warning time scenario. Cases with questionable data were given less influence on the suggested range. The overall limits are intended to represent the upper and lower bounds of fatality rates, between which nearly all case history data falls.

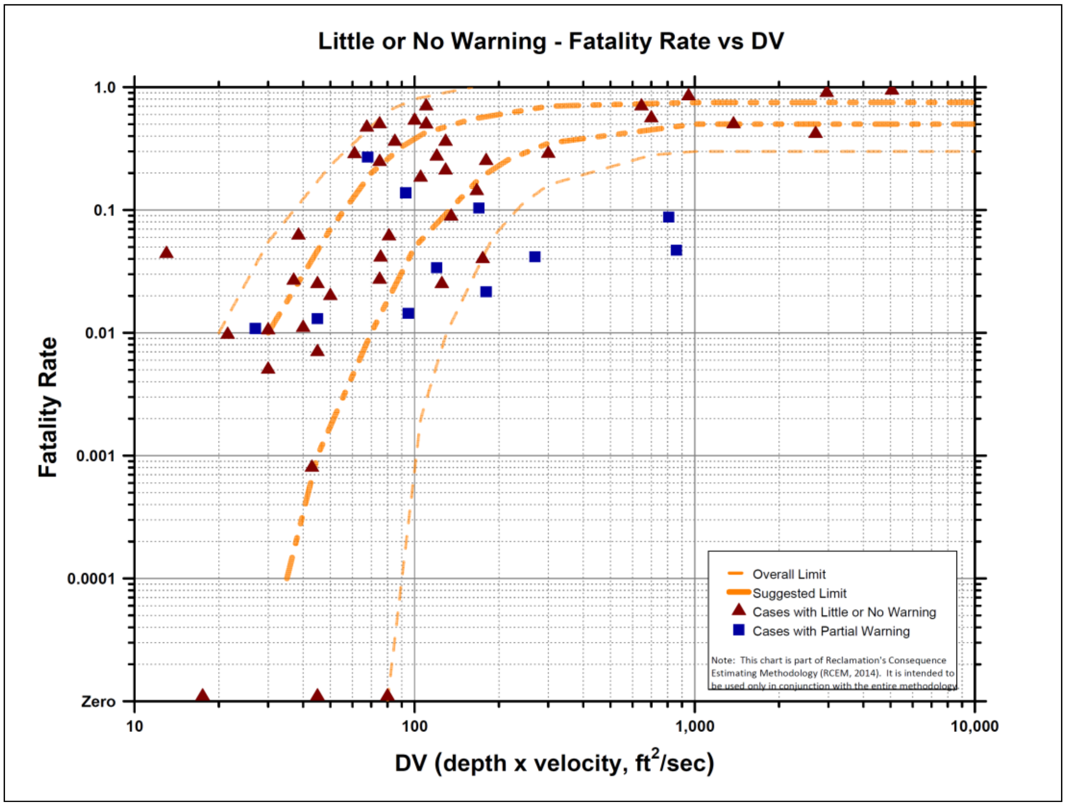

Figure III-1-28. Fatality Rate vs. DV for Little or No Warning

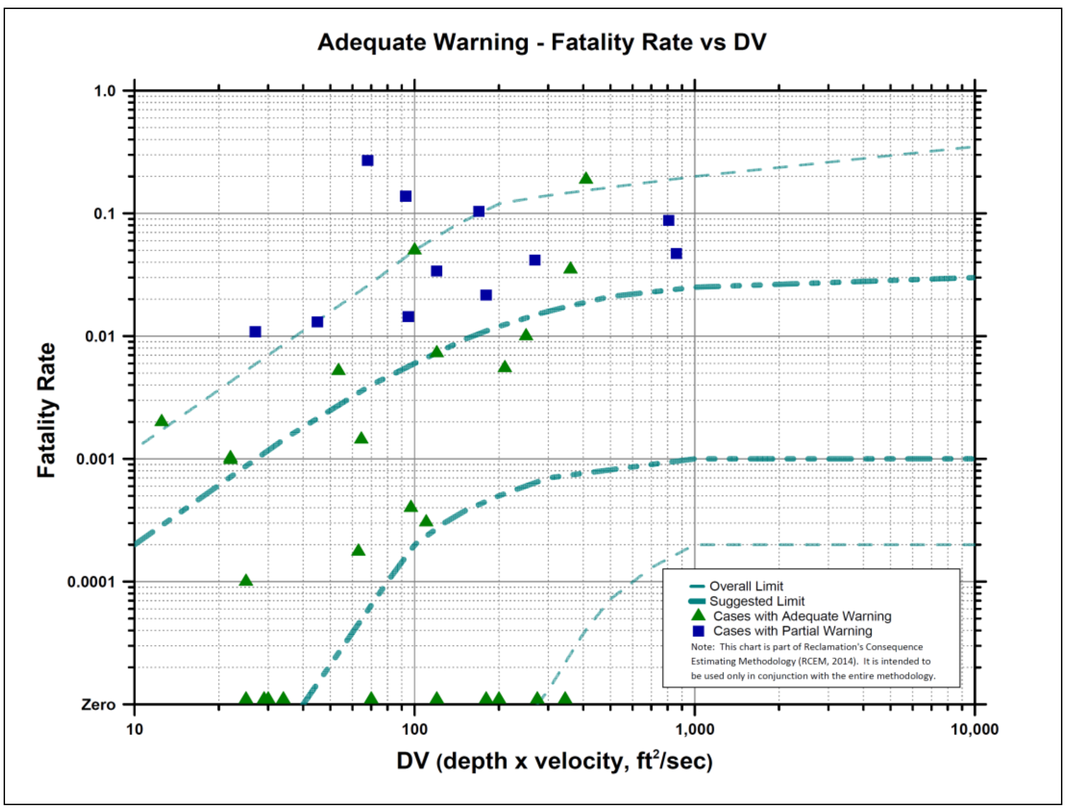

Figure III-1-29. Fatality Rate vs. DV for Adequate Warning

Application of the Procedure

Estimation of life loss resulting from a dam failure requires consideration of many factors - some of the major factors are listed below.

- The potential failure mode (or modes) for the dam
- The assumed breach parameters
- The extent and severity of downstream flooding
- The time of day (or season) of the flooding
- Flood wave travel time
- Assumptions of warning and evacuation
- The downstream population at risk
- The fatality rates

The full consideration of all these factors is a complex problem that requires (1) detailed modeling of the physical processes (breach characteristics and flood routing), (2) estimation of human responses, and (3) the estimation of the performance of technological systems and structures such as warning and evacuation systems, transportation systems and buildings under flood loading. Using empirical data from case histories of dam failures and other similar events, RCEM provides a practical approach to this complex problem of estimating life loss for use in dam safety risk analysis.

The procedure for estimating life loss involves completion of 10 tasks as summarized on Table III-1-6 below. A discussion of each task is included in the paragraphs that follow. Note that with most tasks, the selected values should be justified (a case built for the estimates or assumptions).

Table III-1-6 Summary of Tasks for Estimating Life Loss

Task	Description
1	Select dam failure scenarios (e.g. sunny day, flood, etc.) that correspond to dam potential failure modes
2	Select appropriate time categories (e.g. day/night, seasonal, weekend/weekday, etc.)
3	Review and evaluate flood inundation mapping and define appropriate reaches or areas flooded (by river reach, town, etc.) for each dam failure scenario
4	Estimate flood severity range (i.e. DV range) for the flooded areas. Some towns or river reaches may have PAR in different flood severity ranges, depending on the flood characteristics. Justify the estimates.
5	Estimate the population at risk (PAR) within each reach for each failure scenario, flood severity range, and time category. Justify the estimates and provide any referenced resources.
6	Estimate when dam failure warnings would be initiated (depends on many factors, suggest using range). Estimate the warning time category for flooded areas (e.g. little to no warning, adequate warning, or between the two). Justify the estimates.
7	For each PAR reach, use the graphical approach to estimate an appropriate fatality rate range based on flood severity, warning time and other

	considerations. Justify the estimates.
8	Estimate life loss range for each PAR reach by applying appropriate fatality rate range limits to each PAR. Sum the life loss estimates for each PAR to get the total estimated life loss range. Estimate life loss range for different dam failure scenarios as needed in Task 1.
9	Evaluate how uncertainties and variability in various parameters affect overall uncertainties in life loss estimates. Perform sensitivity studies if needed. Identify areas of higher and lower uncertainty.
10	Build the case for the life loss estimates by documenting all assumptions and references used. Discuss confidence in the life loss estimates.

Task 1 – Select dam failure scenarios (e.g. sunny day, flood, etc.) that correspond to dam potential failure modes

The loss of life caused by dam failure flooding may be highly dependent on the potential failure mode, which includes consideration of any loading being applied to the structure and the response of the structure to the loading. Failure scenarios for dam safety risk analysis are typically identified from the findings of a Potential Failure Mode analysis. For the purposes of dam safety risk analyses, potential failure modes usually fall into three categories: static, seismic, and hydrologic. While there may be a significant range of dam failure scenarios, it is not necessary to estimate life loss for every scenario; similar dam failure scenarios can be grouped together and the estimated life loss range can capture some of the variability in the dam failure scenarios.

In general, when considering the dam failure scenarios to select, it is the estimated breach outflow that is the primary driver. Different potential failure modes may have similar, or widely varying, breach outflows. In addition, the speed with which the breach develops can impact many key life loss estimating factors such as warning time, size of inundation area, and flood severity.

Task 2 - Select appropriate time categories (e.g. day/night, seasonal, weekend/weekday)

The first step in this task is to evaluate if various time categories are needed to estimate life loss. In general, different time categories may be needed if the PAR varies significantly over time. If there is no significant variation in PAR over time and there are very long warning times for downstream populations, then a judgment can be made that there would not be a significant difference between day and night conditions. In this situation, only one time category is used for the life loss estimate.

The time of day, day of week, and month or season during which the dam failure takes place may strongly influence the resulting loss of life. Case histories of dam failure flooding events have shown that warning and response can be much weaker during nighttime hours, resulting in significantly higher fatality rates. The time of day can have a significant influence on life loss for situations where the PAR is very close to the dam, and less of an influence where the PAR is many hours downstream. Consideration of different time categories can help with sensitivity analyses and can help estimate ranges of PAR and life loss.

PAR is typically considered to consist of permanent residents and transient population such as recreationists. Transient PAR is usually assumed to be much more variable than residential PAR; for example the transient population may decline greatly in winter when recreation opportunities along a river may be limited.

Task 3 – Review and evaluate flood inundation mapping and define appropriate reaches or areas flooded (by river reach, town, etc.) for each dam failure scenario

Flood inundation modeling is a critical part of the life loss estimation process. The flood inundation model provides estimates of the inundation areas, the severity of flooding, and flood wave travel times. It requires assumptions about the type of breach that will occur.

Flooded areas downstream from the dam can be divided into several different locations or river reaches. When deciding how to divide the inundation area, the following factors should be considered:

- Residential versus transient PAR;
- Occupancy type (e.g., tent in a campground versus one-story dwelling);
- Varying occupancy considering season, time of day, or other factors (e.g., manufacturing facilities, summer resort areas, campgrounds, picnic areas);
- Population density (e.g., scattered residences, small town, large city);
- Flood characteristics (i.e., flood depths, DV, rate of rise);
- Warning characteristics (i.e., timing, amount, and quality).

Areas with similar characteristics should typically be combined into a single reach.

Task 4 – Estimate the flood severity range (i.e., DV range) for the flooded areas

Flood severity has a significant influence on fatality rate. In general, case history data indicates that the highest estimated fatality rates are associated with the highest estimated DV values. When the flood severity is lower, there is greater observed scatter in the fatality rates, most likely because other factors have a greater influence at the lower DV values.

Flood severity is quantified in terms of depth multiplied by velocity of flow, or DV. Although the parameter DV is not necessarily representative of the depth and velocity at any particular structure, it is representative of the general level of destructiveness that would be caused by the flooding. DV increases as peak discharge from dam failure increases, or it may decrease as the width of the inundated area increases.

Most commonly, DV can be quantitatively estimated at any location by dividing the flood flow (ft^3/s) by the flood width (ft), or by multiplying maximum flood depth and maximum velocity as obtained from hydraulic modeling output information. However, there are a number of ways that DV has been, and can be, estimated depending on the availability of flood information. Since RCEM features the use of a log scale for the data, relatively small ranges in the DV parameter (perhaps factors of 2 or 3, for example) may not significantly impact the fatality rate, depending on the location in the curve where the values fall. Although it is important to estimate DV as carefully as possible, it is not critical that the resulting calculation is completely "accurate." Rather, a range of DV can be estimated using different approaches and with varying input assumptions. In fact, the actual DV values in a given flood reach probably do vary appreciably, so providing a range may be the best way to represent conditions. In most cases, this range can be used with the graphs to come up with a reasonable fatality rate range.

Task 5 – Estimate the population at risk (PAR) within each reach for each failure scenario, flood severity range, and time category

After DV values have been estimated in each flooded area, the PAR in each area is estimated. For each combination of failure scenario, flood severity category, and time category identified in Tasks 1, 2, and 4, the number of people at risk is estimated. PAR is defined as the number of people occupying the dam failure flood plain prior to the issuance of any warning or evacuation.

At a very basic level, the development of a PAR estimate can be as simple as visiting the area downstream of a dam and counting houses in the inundation zone. PAR can also be obtained using the inundation mapping data overlain with census data. A geographic information system (GIS) is a powerful tool that can be used to simplify this process. The most accurate data for residential PAR estimation is at the level of the census block. When the flood inundation boundary can be overlain with the census block data in a GIS, the number of inundated PAR households can be calculated. Partially inundated census blocks must be treated separately. If the residences are evenly distributed within the partially inundated block, a percent inundated estimate can be applied to the total number of households within that block. If the distribution of residences within a partially inundated block is more concentrated in specific locations, then the recommended approach would be to manually count the houses (identified in aerial imagery) in the inundation zone. Finally, the total number of inundated residences is multiplied by an average household size that is specific to the area of interest (which can be obtained from census data), to obtain the estimated residential PAR.

Task 6 – Estimate when dam failure warnings would be initiated and estimate the warning time categories for flooded areas (e.g., little to no warning, adequate warning, or between the two)

Warnings refer to either specific notification of a developing or already in progress dam failure issued by public officials, or an informal recognition and awareness of a developing threat, perhaps passed by neighbors or simple observations of changing river conditions.

In the most ideal situation, a dam breach in progress would be detected, well in advance of the beginning of catastrophic outflows, and warnings and a strong evacuation order would be issued to downstream PAR without delay, with all of the PAR moving safely out of the flood zone by the time flooding arrives downstream. Dam failure and flash flood case histories indicate the ideal situation does not always develop. The sequence of events that takes place is often a mix of physical and social phenomena combined with some element of chance or luck.

The recognition of a developing dam failure and the possible issuance of warning by officials and subsequent PAR decisions regarding evacuation are critical factors that impact the potential for life loss. However, an equally important consideration is flood wave travel time, or how long before the dam failure flooding actually reaches a given downstream reach.

Flooding case histories show that, in general, the number of fatalities decreases as the distance downstream increases, but increasing distance by itself is not what decreases the life loss potential. Potential life loss decreases when the travel time begins to exceed the amount of time required to warn and evacuate the PAR. (Evacuation, or the lack thereof, is accounted for in the fatality rates (using the pre-evacuation PAR) described in Task 7.) Another result of increasing distance is the attenuation (reduction) in flow that occurs. However, flow depths and velocities can increase downstream if the flood plain transitions from a wider valley to a narrow canyon.

Assumptions regarding when formal or informal dam failure warnings for a particular dam would be initiated can be based on an analysis of the monitoring/detection (including the likelihood that anyone will observe a changing condition), decision making, and notification systems or procedures for the dam. In many cases it may be appropriate to estimate reasonable best case and worst case situations to bracket the time when warnings would be initiated. This range of values can be used to estimate a range of warning times.

The case history data generally indicates higher fatality rates for less warning time, and vice versa. However, because of the large number of factors that influence each case, similar fatality rates may result from different cases with different warning times. For the purpose of estimating warning time using RCEM, two warning time categories are used:

- Little to no warning (typically less than an hour)
- Adequate warning (typically more than an hour, although there could be situations with a dense population where hours of warning are not adequate)

After estimating the warning time range for each location, a judgment is made as to which warning category would best represent that location. The distinction is important because in Task 7, fatality rates are estimated using either a chart for "little to no warning" or a chart for "adequate warning." The exact determination of how many minutes or hours of warning is not as important as the general category selected. As discussed below under Task 7, the expected warning time (and quality) is a consideration (along with other factors) when selecting the upper and lower limits of the recommended and overall fatality rates.

Task 7 – For each PAR reach, use the graphical approach to estimate an appropriate fatality rate range based on flood severity, warning time and other considerations

This task involves using all of the information available for a dam failure scenario to estimate fatality rate ranges for each PAR area. For PAR areas that are assumed to receive little or no warning, Figure III-128 is used, and for PAR areas that are assumed to receive adequate warning, Figure III-1-29 is used. Each chart includes dashed lines that represent "suggested" and "overall" limits for fatality rates over the full range of DV values. The suggested limits provide a starting point for estimating the fatality rate range. The selected fatality rate can be increased or decreased, based on all of the relevant factors for each specific PAR area. The full limit ranges shown are not intended to be used by estimators directly, but rather they are intended to help the estimator interpret the approximate data trends from the case histories. For example, the range of overall limits for little warning and a DV of 100 ft^2/s covers about three orders of magnitude; however, it is unlikely that the range of uncertainty in the fatality rate selected would span that full range. Typically, the selected fatality rate range would be expected to span about one order of magnitude. Judgment should be applied and a case should be built for selecting a fatality rate range that is most appropriate for the situation being evaluated. The application of judgment can include: comparison to relevant case histories, site specific topographic/geographic/demographic considerations, evaluation of relative changes in flow characteristics for a given reach when compared to an upstream reach, assumed differences in warning time between subsequent reaches, and the potential for evacuation. Judgment can also be applied between various potential failure modes in terms of differing flow characteristics and anticipated warning times. It is acceptable to use a fatality rate range with limits above or below the overall limits, as long as a case is built for the estimated range, particularly that portion of the range that is beyond the limits of the case history data.

Task 8 – Estimate life loss range for each PAR reach by applying appropriate fatality rate range limits to each PAR reach

The range of estimated life loss for each specific PAR reach (corresponding to a location, warning time, or flood severity) is determined by simply multiplying the appropriate fatality rate range limits by each PAR estimate. For each dam failure scenario, the life loss estimates from each PAR reach are summed to get the total estimated life loss range.

In addition to providing the range of total fatalities, a “best estimate” should be provided. This best estimate may be the mean, a value derived by using suggested point values within each reach, or a weighted average between seasonal or day/night combinations. There is no “correct” way to determine this best estimate; it is up to the estimating team to build a case for how to best represent the best estimate within the total estimated life loss range.

Task 9 - Evaluate how uncertainties and variability in various parameters affect overall uncertainties in life loss estimates

As evidenced by case histories, there can be a large range of fatality rates from dam failure flooding. This is not surprising, considering the variability in PAR, severity of flooding, and warning time. However, even within a given category of flood severity or warning time there can still be a wide range of fatality rates. These differences may result from having some of the PAR located near the river and some of the PAR located farther away and thus less likely to feel the brunt of the flood flows. Similarly, not all warnings are issued in the same manner, and different populations may respond quite differently to warnings.

The graphical approach features “overall” limits to observed fatality rates; these are essentially envelope curves that cover the majority of case history data points. Within the overall limits are a set of “suggested” limits. Even these suggested limits typically show significant differences between the upper and lower curve. Thus, case histories confirm the uncertainty and variability inherent in the potential loss of life due to flooding. It is important to recognize this uncertainty, and properly reflect it in final estimates by portraying life loss as a range, often with an order of magnitude difference between upper and lower bounds. In addition, the estimating team should consider what type of probability distribution should be applied to any reported range. It is not unusual for a life loss range to be reported as a uniform distribution, which implies that the life loss really could fall anywhere within the range with equal likelihood. This would result in a mean estimate in the middle of the range, reflecting a belief that the team finds no compelling reason that the life loss would be expected to fall in either the high or low end of the range.

Sometimes, the confidence in an estimate, as well as an understanding of uncertainty, can be enhanced by a simple sensitivity analysis. Instead of assuming only a point estimate for a particular parameter in a consequences analysis, a range in life loss can be calculated by assuming different values for that variable. Approaching a life loss evaluation in this manner will likely provide a better idea of the potential range of life loss to be expected, as well as improve the confidence in the estimate.

Task 10 – Build the Case for the Life Loss Estimates

Building the case for the selected life loss estimates is a key requirement. The case for the life loss estimates should address the key inputs that are included in the preparation of the loss of life estimates, including: available inundation studies and the failure scenarios and breach assumptions that they are based on the flow characteristics defined by the inundation studies, the accuracy of census or other information used to estimate the population at risk along the inundated area, the basis for assumptions of when warning would be issued, any limitations on warning effectiveness and/or evacuation of the population at risk, any unique site specific factors, and an overall rationale for the selection of fatality rates. The case for the consequences should convince the reader and ultimately the decision makers that the loss of life estimates are reasonable.

The case for the loss of life estimates should discuss the uncertainty inherent in the estimates and the confidence that the risk analysis team has in the estimates. If sensitivity studies indicate only small differences in the life loss estimates, confidence will be higher in the estimates. Even if the loss of life estimates are sensitive to the assumptions, if the overall dam safety findings are not changed based on the sensitivity studies, the overall confidence in the findings may remain moderate to high. For example, although the life loss estimates may vary by a factor or 2 or 3 depending on assumptions (indicating a lower confidence in the estimated life loss), the total annualized life loss estimate may still remain in the area indicating decreasing justification to take action.

Summary

The estimation of life loss that might occur as a result of dam failure is a difficult task, involving considerable uncertainty. Since the 1990s when Reclamation began utilizing quantitative risk analysis as a tool to evaluate dam safety, life loss estimation has been based on an empirical approach that utilized data from past flooding events. These data illustrate the wide range of possible fatality rates that can occur during flooding events, and provide valuable data and insights that can be applied in estimating potential life loss from future dam failures. RCEM continues to be based on case histories, but has been enhanced through the addition of many more historic flooding cases, as well as plotting the data points in a way that illustrates the range of fatality rates observed in the case history database. Engineering judgment and careful consideration of site-specific conditions and potential failure modes are stressed as key requirements for application of RCEM.

Example Application of RCEM

The RCEM Examples of Use document includes four examples of application of the methodology.

Life Safety Model

While the standard approach for Reclamation is to use the new empirical methodology for estimating loss of life consequences, Reclamation does see a key role for the use of numerical models. These tools are very useful for identifying possible scenarios that might develop when large urban populations are subjected to dam breach flood flows. Under these conditions, the models are useful for identifying the potential for successful evacuations and for providing a better understanding of the distribution of a mobile population at risk when the flood wave hits.

Reclamation has started using the Life Safety Model (LSM), on a very limited basis, to address dam failure scenarios which involve the evacuation of densely populated urbanized areas. Urbanized residential areas present unique problems when attempting to estimate life loss due to dam failure. The LSM has been used to simulate evacuation patterns and traffic congestion in urbanized environments. The LSM considers the movement of water and its interaction with persons who may be located within structures, or in motor vehicles and on foot. Fatalities are estimated based on criteria involving flood depths, velocity and exposure periods. Safe havens are pre-designated, and can be located both within flooded areas and on its fringes.

Models that are based on empirical case history data (such as RCEM) are limited in that there are no well documented dam failure events which have affected large population urban communities. Simulation models such as the LSM attempt to fill this void.

The effects of flooding on structures, cars and people are evaluated in terms of critical hydraulic parameter thresholds such as depth, and DV. In the LSM “Object Damage and Loss Functions” (ODLF’s) have been developed to define how objects interact with the flood. This mathematical function considers if an object is gradually weakened by prolonged exposure to the flood (which reduces that individual’s ability to move or rate of movement), incapacitated by the flood (weakened to a point of immobility or “floating”), or immediately lost by contact with the flood (critical DV).

In a typical LSM simulation, population at risk can become aware of an impending flood situation and may attempt to evacuate either in a motor vehicle or on foot to a pre-designated “safe haven”. Evacuation during an LSM simulation takes place over a road network, with a basic transportation model being implemented to estimate characteristics of traffic flow. Fatalities can occur if the flood depth or DV threshold parameters are exceeded for building structural stability, toppling of a motor vehicle, or toppling/submergence of an individual attempting to flee on foot.

Figure III-1-30 shows and example LSM simulation. In this example, the evacuees are color-coded according to status. The black points are persons (actually household groups of persons) who are unaware, yellow is aware, but not yet evacuating, green is for those who are in the process of evacuation and red is evacuees who have become fatalities due to exposure to flooding.

Figure III-1-30. Example LSM Simulation

The LSM was originally developed by BC Hydro of Canada, with assistance from the Canadian Hydraulics Centre, a division of the National Research Council, Canada [2]. Current development of the LSM is now facilitated by HR Wallingford of the United Kingdom.

LSM simulations require the following input data in digital format 2D hydraulic modeling output data, road network data, building location data, and initial locations of population at risk (expressed as either individuals or as groups). The use of the LSM within Reclamation is still at a preliminary level. Application of the LSM to date has been for the estimation of fatality rates for consequence analysis which involves high severity flooding with warning, a case for which empirical-based methods offers limited guidance. The value of the LSM seems to be for applications where traffic congestion during evacuation is a significant issue. These are special cases for which the extra time and expense of LSM analysis is appropriate given a high potential for life loss. For these cases, there is value in gaining a clearer understanding of how evacuation may play a role in the number of fatalities.

USACE Life Loss Estimation Methodology

Historically, development of life loss estimates for dam or levee failure scenarios has been has not been common within USACE. Traditional dam safety management practices only considered consequence estimates when making project specific modification decisions, and those were usually limited to property damages. Detailed life loss estimates were seldom required to support these decisions since a dam safety modification could be justified simply by demonstrating the potential for one or more fatalities. The priority and relative magnitude of dam safety issues under past USACE practices was primarily focused on performance and adherence to design standards and did not explicitly consider the potential consequences of failure. As a result, dam failure consequence estimates for most dams (and levees) within the portfolio do not exist, are outdated, or lack sufficient detail to adequately inform the USACE portfolio management activities.

USACE promotes a scalable, decision-driven process for estimating consequences due to dam or levee breach. That process implies that the level of detail and accuracy for a given analysis must be appropriate to support the decision being made within a reasonable level of confidence. For example, a screening level assessment could be used to support an initial ranking for a portfolio of dams or levees via the USACE Dam or Levee Safety Action Classification. This classification level could then be used to set priorities for more detailed studies. This initial screening level assessment should require significantly less effort and rigor than that for a detailed assessment used to determine what risk reduction actions are needed to satisfy tolerable risk guidelines. The relative accuracy required to get a "right" answer must not be taken out of the context of the decision to be made. Too much effort can divert limited resources away from other critical dam or levee safety needs just as too little effort potentially leads to poor decisions. The decision driven nature of this risk process requires methods that can be easily scaled to the appropriate level of effort needed. The life loss estimations tools used by USACE, described below, fit the requirements of this scalable, decision-driven approach.
Since most decisions being made within the Dam Safety and CIPR Programs are initially life safety related, the focus of this paper is on the methodology applied by USACE for estimating population at risk (PAR) and loss of life.

Limitations of empirical approaches such as RCEM, DSO-99-06 and others that preceded it are widely recognized and have resulted in the development of simulation-based approaches to estimating loss of life. USACE, along with Reclamation and other agencies, funded researchers at Utah State University to develop one such simulation methodology known as LifeSim in the early 2000s. USACE has continued development of this methodology and GIS based tools that can be used to apply the methodology for dam or levee safety consequence assessments.

It was recognized early on that application of LifeSim can be very resource intensive. Therefore, in order to satisfy the scalable, decision-driven approach described above, a simplified version of LifeSim was developed and included in the *Hydrologic Engineering Center's Flood Impact Analysis* program (HEC-FIA). The LifeSim and simplified LifeSim (HEC-FIA) procedures described herein are based on the foundation of knowledge gained from an in-depth analysis of case histories conducted by D.M. McClelland and D.S. Bowles.

Requirements for a typical application of LifeSim or HEC-FIA can be met from readily available data including Census, FEMA’s HAZUS-MH, USGS Seamless and output from a dam or levee breach inundation model, such as HEC-RAS, FLO-2D or any other hydraulic model that generates results suitable for GIS processing.

As defined within the LifeSim framework, estimation of the magnitude of life loss resulting from a dam or levee failure, whether due to a major natural event (such as a flood or an earthquake), a design or construction defect, or a successful adversarial attack, requires consideration of the following three groups of factors:

- **The flood event,** including specific characteristics of the initiating event (i.e. for flooding cause by dam or levee breach the following factors are important: the breach location, geometry and rate of breach development, the water level behind the dam or levee, the time of day, detection time of the breach-event relative to breach initiation, and the extent, velocity, depth and arrival times throughout the downstream inundation area.
- **The number and location of people exposed to the flood event**, including the initial spatial distribution of people throughout the inundation area, the effectiveness of warnings, the response of people to warnings, the opportunity for and effectiveness of evacuation, and the degree of shelter provided by the setting where people are located (structure, vehicle, on foot, etc.) at the time of arrival of the flood water.
- **The loss of life amongst the threatened population** who remain in the inundation area at the time of arrival of the flood water. Loss of life estimates at a specific location take into consideration the physical character of the flood event and the degree of shelter provided by the setting where people are located at the time of arrival and after the flood wave has passed for those who survive it.

Clearly, the full consideration of all these factors is a very complex problem that requires detailed modeling of the physical processes (breach characteristics and flood routing), human responses, and the performance of technological systems (such as warning and evacuation systems, transportation systems and buildings under flood loading).

USACE Inundation Modeling

USACE studies typically use the Hydrologic Engineering Centers River Analysis System (HEC-RAS) to model dam and levee breach scenarios. HEC-RAS is a software tool that performs one or two-dimensional steady and unsteady flow river hydraulics calculations, sediment transport-mobile bed modeling, and water temperature analysis. HEC-RASis endorsed by the USACE Hydrology, Hydraulics, and Coastal Community of Practice (HH&C CoP), receive continued support within the agency, and is freely available for downloading from the HEC website (www.hec.usace.army.mil). The link between HEC-RAS or similar hydraulic tools and GIS facilitates the use of readily available and existing data sets, efficient model development, and processing of results. New data and information can be readily incorporated into existing models when improved accuracy is needed. Once a current georeferenced HEC-RAS model is available for a dam, the models can be updated as necessary when new information is available.

HEC-FIA (Simplified LifeSim)

The Simplified LifeSim methodology is applied within the HEC-FIA software program. The applicability depends on the goals of the assessment as well as the characteristics of the study area. The main differences between the Simplified LifeSim methodology applied within HEC-FIA and the LifeSim methodology are as follows:

Evacuation Simulation - Simplified LifeSim uses a basic evacuation model where the user either provides the amount of time required for inhabitants of each structure to evacuate to safety or provides a hazard boundary in the form of a polygon shapefile. If a hazard boundary is provided, HEC-FIA determines the shortest straight-line distance from a structure to the hazard boundary and applies a nominal evacuation speed along that line to estimate the amount of time required to evacuate. The effect of traffic jam potential must be accounted for implicitly by the choice of the nominal evacuation speed. If the loss of life for a study is highly dependent on evacuation efficiency, including the effects of traffic congestion, application of the full version of LifeSim should be considered as it contains a more detailed evacuation model.

Arrival Times - In Simplified LifeSim, flood arrival time at a structure is computed by interpolating cross-section hydrograph output from a one-dimensional hydraulic model or from a grid that contains arrival time values. The full version of LifeSim computes flood wave arrival time by accessing a time-series of depth and velocity grids for the entire flood event throughout the inundated area. Both models can utilize output from a two-dimensional model.

HEC-FIA Inputs

A technical description of the process and computations contained in HEC-FIA to estimate life loss following the Simplified LifeSim methodology is provided later in this paper. For instructions on using HEC-FIA, download the HEC-FIA User's Manual from www.hec.usace.army.mil. Inputs required by HEC-FIA to compute life loss and direct property damage are described below:

Digital Elevation Grid: A digital elevation grid is required to compute consequences in HEC-FIA. The digital elevation model is used to assign elevations to structures as well as the elevation of the safe location in the evacuation effectiveness computation. The digital elevation model used in HEC-FIA should be the same as the one used to develop the hydraulic model of the dam break.

Structure Inventory with Population: All life loss estimates in HEC-FIA are done on an individual structure basis. Therefore, an inventory that represents all the structures within the flooded area is required. Each structure must have a ground elevation and population assigned to it at a minimum, but the height of the structure is also important (1-story, 2-story, etc).

If a detailed structure inventory does not exist for the study area, capabilities available in HEC-FIA allow the user to generate a structure inventory for an area using an existing parcel database (shapefile) or the database that comes with the FEMA HAZUS-MH tool. When a structure inventory is generated using the HAZUS data, it should be checked against aerial imagery to insure that it is representative of the study area.

The number of people in a structure often varies between day, night, weekday, and weekends in residential, commercial and industrial areas. Population in a structure or area can also vary significantly on a seasonal basis for campgrounds and other types of recreational facilities, or areas of high tourism. Therefore, it is desirable to consider a range of different exposure cases to capture the temporal variations in the numbers of people in a structure. The number of people estimated in each structure should apply to the time that an official public warning to evacuate would be issued for a dam failure for each failure event that is considered. It is important to consider the fact that certain flood-initiated failure events occur only during a specific season of the year and that the range of reservoir pool elevations is commonly highly correlated with season of the year. Capabilities available in HEC-FIA allow the user to generate day and night populations for an existing structure inventory using the most recent census data (HAZUS). Day and night populations estimated by HEC-FIA take into account the shift of population in an area due to working in or out of the area during the day and returning home during the evening and other similar considerations. Additionally this methodology splits the population into the category of being over or under the age of 65 since those individuals over 65 have been shown to be at higher risk of life loss in flood events. In this methodology the population distribution between day and night on weekends is being treated to be the same as during the weekdays.

Seasonal considerations and development that has occurred since the most recent census are not included in the default population distribution provided by HEC-FIA. For areas with high seasonal variability, the population in HEC-FIA will be based on the "permanent" population of the area that is representative of the number of people that identified that location as their primary residence in the most recent census. The user has the ability to define population increases and decreases at the impact area level, which could represent neighborhoods, towns, or counties. Another way to approximate the effects of seasonal variations in population or population changes is to take the final life loss results computed by HEC-FIA and factor them up or down as appropriate. Transient population (i.e. campground and other recreation) should be considered explicitly and included as appropriate when developing estimates for PAR. In HEC-FIA, structures should be added to the inventory to represent tents or campers in a campground. They will not be added automatically from the HAZUS inventory. Population should also be added to those structures.

Recreational PAR for a campground should be based on visitation information for impacted downstream recreation areas (not the ones around the lake which are considered in project benefits foregone) and the duration of average visit when available. For Corps facilities this information can be wholly or partially provided by the host district. These types of statistic are often available in the Operations and Maintenance Business Information Link (OMBIL) data file.

Inundation Data for Each Flood Scenario: The Simplified LifeSim methodology requires an estimate of the time of arrival of the flood wave for each structure. The arrival time represents the end of the opportunity to evacuate a structure, and by default, is defined in HEC-FIA when the depth initially becomes greater than 2 feet and it is assumed that people will choose to evacuate vertically in a structure instead of trying to move horizontally to a safer location once that depth is achieved at a structure.
There are two methods for estimating and entering flood wave arrival times in HEC-FIA. Currently, for dam breaks modeled with HEC-RAS, the most efficient procedure for estimating flood wave arrival time is to use hydrograph output at each cross-section and

storage area. HEC-FIA contains capabilities to load cross-section and storage area geospatial information used in the HEC-RAS model, and access the corresponding HEC-DSS (Data Storage System) files to determine the time at which the flooding depth first reaches 2 feet at each cross-section. It linearly interpolates the arrival time at the structure using the station information of the structure and the upstream and downstream cross-sections. For structures that fall within a storage area, arrival times are computed by using the stage hydrograph for that specific storage area (no interpolation is necessary). Since the flood wave progression is highly dependent on the failure/no-failure scenario and the specific failure mode, a different set of hydrographs must be developed and provided for each scenario to properly estimate arrival times.

The other method available for entering flood wave arrival times in HEC-FIA is with an arrival time grid. Arrival time grids can be generated using 2-dimentional hydraulic models, or directly computed through HEC-RAS Mapper, these grids can be used to estimate life loss in HEC-FIA. Each cell in the arrival time grid must contain the time at which the depth in that cell initially becomes larger than 2 feet (or the non-evacuation elevation being analyzed) relative to some specific point in time for the specific failure or no-failure scenario being studied. This relative time needs to be used when defining the time window of a simulation so that the warning issuance can be delivered at the correct time relative to the breach.

Warning issuance: The Warning Issuance Time is defined as the time at which an official evacuation order is released from the responsible emergency management agency to the population at risk. Life-loss estimates are highly sensitive to warning issuance time and other relationships that affect the effectiveness of warning and evacuation processes for the population at risk. There is significant uncertainty in the model parameters that represent these processes. In the typical USACE screening assessment the goal is to obtain "best estimates" for this parameter and other parameters and through the implementation of guidance and a consistent procedure to reduce differences between implementation of these parameters in evaluating and ranking the screening assessments. The actual process of breach initiation, detection, evacuation warning, and dam failure is illustrated in Figure III-1-31 for a dam failure scenario where the breach is detected prior to actual dam failure, although other sequences can be handled in the analysis, this describes the general framework. For the purposes of this discussion, the parameters illustrated in **Figure III-1-31** are defined as follows:

- **Major Problem Acknowledged**: Time when seepage (or evidence related to other failure mode) is determined to be significant enough that dam failure is likely. Successful intervention is no longer considered probable. Leads to notifying public of impending dam failure.

- **Evacuation Notification from dam owner to EMAs**: Time when observed increase in seepage or other failure mode has been determined to be significant enough to notify EMAs to start the warning and evacuation process.

- **Failure**: Time when rising limb of flow hydrograph through breach begins to increase rapidly. Represents time corresponding to "Trigger Failure" parameter in HEC-RAS dam breach input.

- **Warning Opportunity Time Window:** Amount of time between when the dam owner discovers significant seepage progression that could lead to impending dam failure and actual Failure. Positive value if significant evidence related to failure mode is discovered prior to failure initiation, negative if after failure.

- **Breach formation time:** Amount of time between Failure and when breach reaches full width and depth. Corresponds to "Full Formation Time" parameter in HEC-RAS dam breach data.

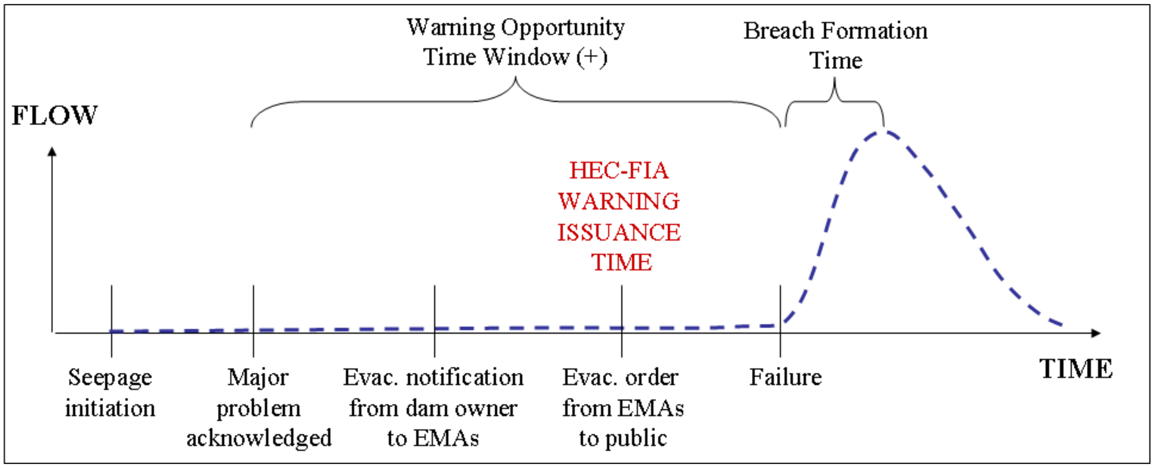

Figure III-1-31. Detection and warning timeline for observed seepage failure scenario

For most failure modes where the failure progress is observable prior to catastrophic failure of the dam, warning issuance times should be determined by first estimating the time when a major problem would be acknowledged relative to the time of dam failure. The major problem acknowledgment time for these failure modes is the time at which a dam owner would determine that a failure is likely imminent and they would decide that the dam breach warning and evacuation process should be initiated by notifying the responsible authorities. The time lag between major problem acknowledgement and when an evacuation order would pass from the dam owner to the responsible emergency agency (EMA) and then from the EMA to the public (Warning Issuance Time) should be estimated based on the judgment of dam operations personnel and emergency management personnel who have jurisdiction in the areas of each downstream community. In obtaining input from operations personnel and emergency management personnel it is important to carefully describe the dam-failure scenario, including the key assumptions that define the development and detection of the failure mode that is considered in each failure event-exposure scenario for which life loss is being estimated, so that they can consider all associated factors in estimating warning issuance times for structures. It is useful to have more than one responsible person involved in this expert elicitation process since different individuals will often think of different important factors and their judgments may vary resulting in a range of estimates of warning issuance times. The process will often result in new ideas for reducing warning issuance times. If a Potential Failure Mode Analysis is being performed, the warning issuance times should be estimated by the group during discussion relevant to each failure mode.

Warning Diffusion Information: The speed of warning dissemination (diffusion) varies between communities and events. Some dissemination channels reach more people more quickly than others. Some types of people are easier to reach than other kinds of people. First alerts/warnings can come from the formal emergency management system, through informal communication processes, or directly from cues in a person's environment. It can be an alert (signal) or a notification (message). Formal alerts and warnings can come via a number of different communication channels involving both new (for example, cell phone or internet) and established (for example, TV, radio, siren, route alert) technologies. Each channel has strengths and weaknesses such as the speed of dissemination, ability to convey information, and susceptibility to failure.

The receipt of an alert or warning is also influenced by the characteristics of the people for whom the message is intended. These include the activities that people are engaged in, where they are located, the time of day, reception impediments, and the personal resources available. Examples are people driving a vehicle and people being in recreational areas when an emergency occurs. Warning diffusion rates are also the impacted by the ability to receive an alert or warning (e.g. if it is nighttime or the intended recipients have hearing impediments.)

The warning dissemination process is provided to HEC-FIA in the form of warning diffusion curves. A warning diffusion curve defines the relationship between time from warning issuance and the percentage of the population at risk that has received that warning.. **Figure III-1-32** displays the potential range in warning diffusion speed based on available research. The different curves are described below:

- Type A: Fast Diffusion Curve – Uses multiple channels including both channels with very fast speeds of alert and broad penetration with frequent dissemination. These are supplemented by channels with high message quality.
- Type B: Moderately Fast Diffusion Curve – Uses multiple channels but not all latest fast technologies.
- Type C: Moderate Diffusion Curve – Uses mix of traditional technologies, but not technologically advanced technology.
- Type D: Slow Diffusion Curve **-** Uses limited technologies with single dissemination.

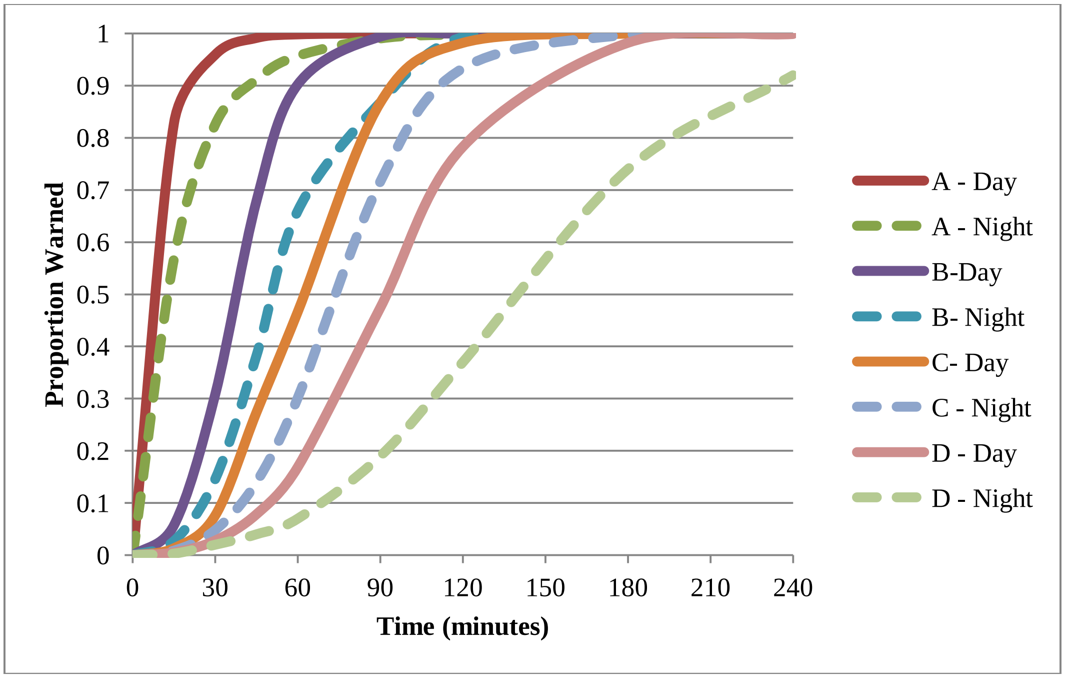

Figure III-1-32. Warning Diffusion Curves

Warning diffusion relationships should be estimated based on discussions with local emergency managers. In many cases it will be necessary to define different warning diffusion curves for different sub-populations. USACE uses a consequence elicitation process to determine diffusion curves. That elicitation process follows guidance from social sciences on the questions that should be asked of the emergency managers and methods for taking their answers and selecting appropriate diffusion curves. Contact the USACE Risk Management Center for an up-to-date consequence elicitation guidance.

Mobilization or Protective Action Initiation Information: Mobilization time, also known as protective action initiation delay time is defined as the amount of time between when a warning is received and when that warned person takes the recommended protective action (e.g. leaving their structure). The mobilization time is defined in HEC-FIA by a mobilization or PAI curve. The mobilization curve contains two important pieces of information for determining the number of people that have evacuated their structures when the flood arrives: (1) the percentage of warned people that mobilize over time; and (2) the maximum mobilization percentage. The maximum mobilization percentage defines the highest percentage of people that it is estimated would attempt to leave the potentially inundated area, given the characteristics of the nature of the potential dam failure, the warning message, and many other factors including cultural considerations and in some cases the effects of past evacuation experiences. One hundred percent minus the maximum mobilization percentage yields the percentage of people that are either unable or choose not to mobilize after receiving the warning. Like warning diffusion relationships, mobilization curves are defined based on results of consequence elicitation. USACE follows a consequence elicitation process that was developed by social scientists familiar with the primary factors that influence mobilization based on available research. The range of mobilization curves defined in that research are shown in **Figure III-1-33**. These curves should be factored by the estimated maximum mobilization percentage prior to input into HEC-FIA or LifeSim. It is recognized that the life loss estimate is highly dependent on the mobilization information provided to HEC-FIA, and that the actual mobilization decision process contains many contributing factors and is highly uncertain. When running HEC-FIA in uncertainty mode, the user can define the uncertainty around the mobilization curves so that the uncertainty around this function can be represented.

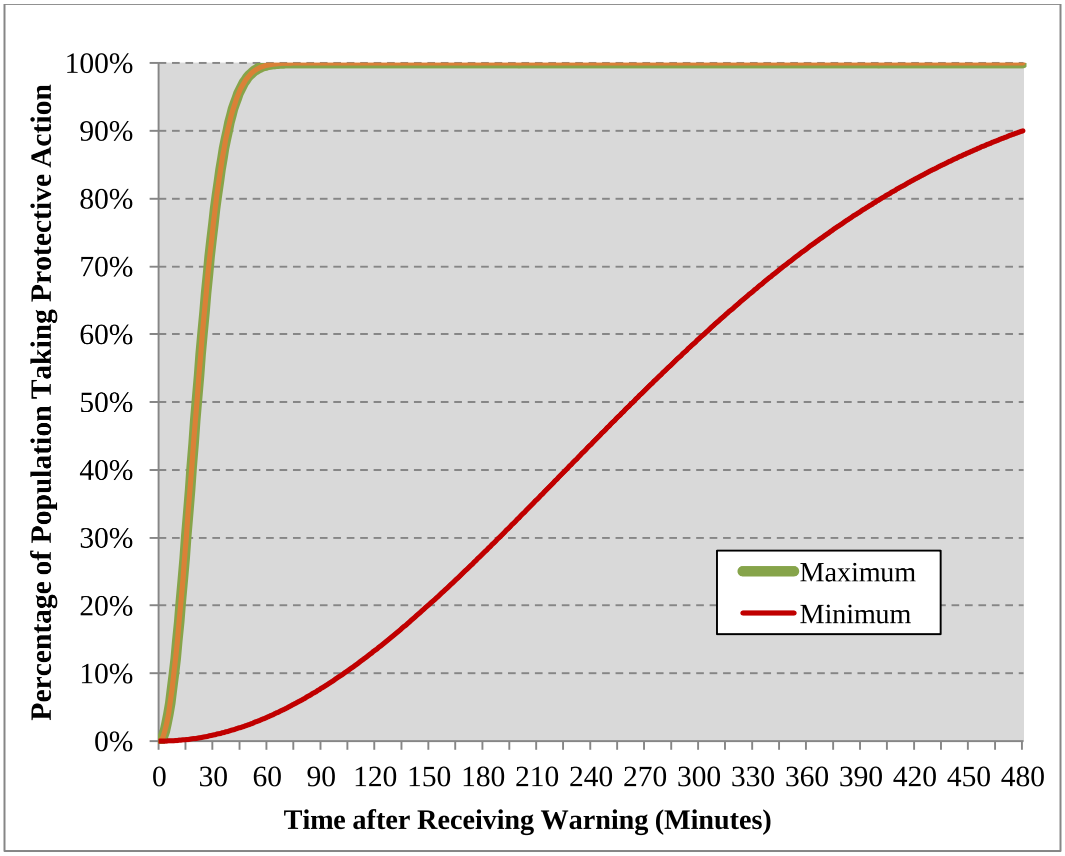

Figure III-1-33. Mobilization or Protective Action Initiation Curves

Evacuation Timing Information: The time required to evacuate depends on many factors, including mobility, the location of shelters, and the capacity of the evacuation route. The full LifeSim model includes detailed dynamic transportation simulation modeling capabilities to obtain estimates of the evacuation process throughout the inundation area (Aboelata and Bowles 2005; Aboelata et al 2005).

For the Simplified LifeSim procedure, it is necessary to either reduce the evacuation process to a straight-line shortest distance process or rely on the judgment of first responders who have jurisdiction in the areas of each downstream community. It may also be useful to consult with managers of facilities such as schools, hospitals, large public gathering places, recreational areas, etc, to obtain their judgments on how rapidly they could complete an evacuation and the extent to which vertical or in-place evacuation would be relied on. As in estimating other inputs, it is important to carefully describe the dam-failure scenario to those first responders and others who are involved in this expert elicitation process to estimate evacuation effectiveness. The user can describe the evacuation time for each structure individually, which gives the user the capability to model evacuation as a pre-process and input the results of evacuation times per structure instead of relying on the assumptions within the model.

For a typical dam failure consequence analysis in HEC-FIA, the following steps can be used to estimate a time required to evacuate for each structure.

1) Assume the safe location is anywhere that the maximum inundated depth for a given flood scenario is less than 2 feet. Create a polygon representing this hazard boundary.

2) Load the hazard boundary into HEC-FIA and provide a nominal speed at which evacuating people could travel along the assumed straight-line distance. This nominal speed is less than the actual speed along the road network because the distance is greater through the road network than along a straight-line path as represented in Simplified LifeSim.

3) HEC-FIA will compute the time required to evacuate by determining the distance from each structure to the safe boundary and then dividing that distance by the nominal speed.

Lethality Zone Parameters and Fatality Rates: Flood (lethality) zones distinguish physical flood environments in which historical rates of life loss have distinctly differed. The LifeSim research resulted in three flood zones for which historical rates of life loss were estimated and these fatality rates are used in HEC-FIA to estimate life loss. Each flood zone is physically defined by the interplay between available shelter and local flood depths and velocities, as summarized below:

- *Chance Zones*: in which flood victims are typically swept downstream or trapped underwater, and survival depends largely on chance; that is, the apparently random occurrence of floating debris that can be clung to, getting washed to shore, or otherwise finding refuge safely. The historical fatality rate in Chance Zones ranges from about 38 percent to 100 percent, with an average rate over III-11 percent.

- *Compromised Zones:* in which the available shelter has been severely damaged by the flood, increasing the exposure of flood victims to violent floodwaters. An example might be when the front of a house is torn away, exposing the rooms inside to flooding. The historical fatality rate in Compromised Zones ranges from zero to about 50 percent, with an average rate near 12 percent.

- *Safe Zones*: which are typically dry, exposed to relatively quiescent floodwaters, or exposed to shallow flooding unlikely to sweep people off their feet. Depending on the nature of the flood, examples might include the second floor of residences and sheltered backwater regions. Fatality rate in Safe Zones is virtually zero and averages 0.02 percent.

As mentioned previously, the Simplified LifeSim approach in HEC-FIA uses velocity to determine if a structure is capable of surviving the flood event. Therefore, assignment to a specific lethality zone for a given structure is based on the maximum instantaneous depth times velocity for survivorship and final depth of flooding at that structure given its ability to provide safe haven, and the height of that structure. By including the height of the structure, the very significant impact of vertical evacuation is accounted for in the Simplified LifeSim methodology.

HEC-FIA assigns lethality zones based on the evacuation outcome for people starting in each structure and the height of the structure. The logic followed by HEC-FIA for assignment of evacuation outcome categories is described below. After the determination of evacuation outcome is made, then lethality zones are determined. Certain parameters in the lethality zone assignment process are set by default in HEC-FIA, but should be reviewed during the application process to insure that they are representative of the study area region:

1) **Cleared**: the people that evacuate safely do not receive a flood lethality zone assignment.

2) **Caught**: the people that get caught evacuating are assigned to the Chance Zone.

3) **Not mobilized**: the people that stay in structures are assigned to flood lethality zones based on maximum instantaneous depth times velocity, maximum depth of flooding over the entire flood event and the height of the structure. The assumption in Simplified LifeSim is that people evacuate to the level above the highest habitable level in the structure (e.g. the roof or an attic).

   a) For any structure: if the depth times velocity exceeds the RESCDam criteria for partial survivorship, the structure will receive either chance or compromised given maximum depth, if the depth times velocity exceeds the RESCDam criteria for total destruction, the category is automatically determined to be Chance.

   b) For any structure: if structure totally survives and event maximum depth < 2 feet or less than the first floor height (fh) of structure, then no flood lethality zone assignment is made and the people are grouped with the Cleared evacuation category;

   c) If 1-story structure where the population is under 65:

      i) if the structure totally survives and event maximum depth $<$ fh + 13 feet then assign to Safe Zone, if structure partially survives, and maximum depth $<$ fh +13 ft then assign to compromised zone, if structure is totally destroyed, then assign to chance zone:

      ii) if the structure totally survives or partially survives the event and event maximum depth $\geq$ fh + 13 feet and $<$ fh + 15 feet then assign to a Compromised Zone, if the structure is totally destroyed, then assign to chance zone;

      iii) else event maximum depth $\geq$ fh + 15 feet then assign to a Chance Zone.

   d) For each additional story, add 9-1 feet to the depth criteria in b) to determine flood lethality zone. Depending on occupancy type the fatality rates for over 65 the lethality zone thresholds can be set lower.

In the Simplified LifeSim Procedure the following average fatality rates are used based on the probability distributions of fatality rates for each Flood Lethality Zone:

- Safe Flood Zone: 0.0002

- Compromised Flood Zone: 0.12
- Chance Flood Zone: 0.91.

The entire probability distributions of fatality rates for each Flood Lethality Zone are used in HEC-FIA when the uncertainty analysis option is selected.

Simplified LifeSim Methodology

The Simplified LifeSim methodology applied within the HEC-FIA program includes the following steps for a selected Event-Exposure Scenario and given structure inventory with population to estimate loss of life. The steps below are illustrated in **Figure III-1-34**.

1) Obtain the **dam-failure flood wave arrival times** for each structure. The arrival time is the time at which the depth of flooding at the location of the structure is estimated to be large enough that the inhabitants of that structure will choose to stay in the structure and evacuate vertically instead of risk leaving the structure. The default value in HEC-FIA is 2 feet. HEC-FIA estimates arrival times for each structure by interpolating them off of the hydrograph data provided at the nearest upstream and downstream location or by selecting it from the arrival time grid in the specific cell where the structure is located.

2) Calculate the **warning time** for each structure by finding the difference between their respective dam-failure flood wave arrival times (from Step 1) and the public warning issuance time. Warning time indicates the amount of time that the population of each structure has to receive a warning and mobilize, and through the warning diffusion curve determine the percent of the population that was warned.

3) Compute the **time required to evacuate** for each structure, which is an estimate of the amount of time it would take for the people in a structure to evacuate to a safe location after they have mobilized.

4) Combine the user defined warning and mobilization curves into one relationship that represents the number of people who have both received a warning and mobilized.

5) Compute the percentage of people in each **Evacuation Outcome Category.** For each structure, estimate the percentage of its occupants that fall into to each of three possible evacuation categories at the time of arrival of the dam-failure flood wave. This estimate computes fractions of people in individual structures. When the results are summed for the inundated area, it will provide an estimate of the total life risk for the specific scenario.

6) For each structure, assign a **lethality zone** to the people in each evacuation outcome category as described in the previous section.

7) Calculate the **overall fatality rate for the occupants initially assigned to each structure** by summing the following fatality rates for each evacuation outcome category

a) The fatality rate for evacuation outcome category 1 (Cleared) is 0.

b) The fatality rate for evacuation outcome category 2 (Caught) equals the percentage of people caught evacuating multiplied by 0.91.

c) The fatality rate for evacuation outcome category 3 (Not mobilized) equals the percentage of people that stayed in the structure multiplied by fatality rate for the flood zone (depends on maximum inundation depth at the structure)

8) Calculate the **life-loss estimate for each structure** by multiplying the initial population of each structure (from Step 2) by its respective overall fatality rate (from Step 7).

9) Calculate the **total life-loss estimate** by summing the life-loss estimates for all structures (from Step 8).

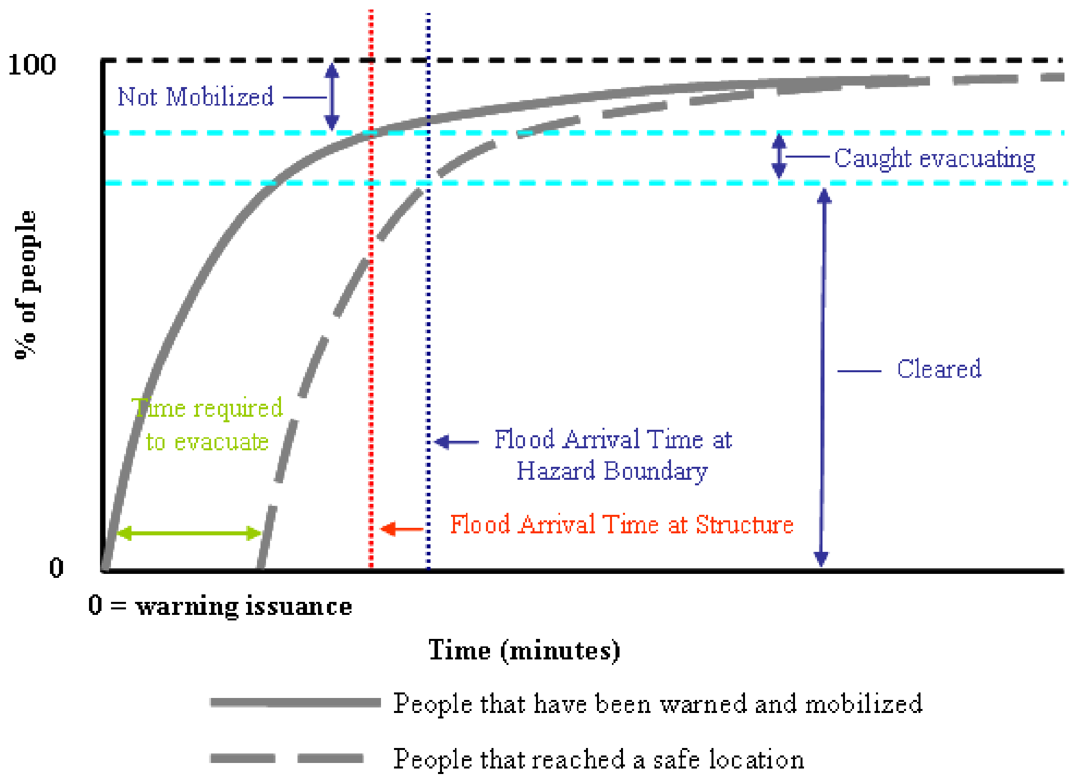

Figure III-1-34. Assignment of Evacuation Outcome Categories

The methodology described above provides a single value or "point" estimate of life loss. Range estimates can be made in recognition of the uncertainty associated with these point estimates. Range estimates can be based on conducting a sensitivity analysis by varying key inputs to the Simplified LifeSim procedure in a sensitivity analysis. The option to run HEC-FIA in uncertainty model provides the preferred approach to obtaining probabilistic estimates using uncertainty analysis if time and resources are justified.

LifeSim

The full version of LifeSim is applied to support risk assessments within USACE when the simplifying assumptions inherent in HEC-FIA result in too much uncertainty in the life loss estimate. Also, given the detailed evacuation modeling available in LifeSim, it is also applied to assist with evacuation planning. Many of the concepts described within the HEC-FIA section above are also applicable within the LifeSim methodology (Lethality Zones, Fatality Rates, etc).

As stated previously, the main difference between the simplified LifeSim approach in HEC-FIA and the full LifeSim methodology is the evacuation modeling. Simplified LifeSim uses a basic evacuation model where the user either provides the amount of time required for inhabitants of each structure to evacuate to safety or provides a hazard boundary in the form of a polygon shapefile. If a hazard boundary is provided, HEC-FIA determines the shortest straight-line distance from a structure to the hazard boundary and applies a nominal evacuation speed along that line to estimate the amount of time required to evacuate. The effect of traffic jam potential must be accounted for implicitly by the choice of the nominal evacuation speed. If the loss of life for a study is highly dependent on evacuation efficiency, including the effects of traffic congestion, application of the full version of LifeSim should be considered as it contains a more detailed evacuation model.

LifeSim uses an agent-based approach to track individuals throughout the warning and evacuation process. It also contains a traffic simulation engine to simulate the evacuation process that allows vehicles to interact with other vehicles and the hazard. The computation engine offers an effective estimation of population re-distribution during the evacuation process. LifeSim was developed with an uncertainty sampling approach. By sampling uncertain parameters and running the model iteratively, LifeSim is capable of producing a distribution of results to better inform a risk assessment.

It is important to note that LifeSim is simulating the entire warning, mobilization, and evacuation process. The process can be illustrated with the following example. Consider a single family home containing 3 people that is located in the study area for a given simulation. Once a flood warning is issued by emergency managers, it takes some amount of time before a resident in the home receives the warning. Once the warning is received and understood at the home, the family members will take some time to gather their belongings and prepare for leaving their home. The family then leaves their home in a car containing 3 people. On the road, they interact with both other vehicles on the road and flood waters. For example, they may encounter a traffic jam at a freeway on-ramp and choose a different route out of the hazard area (see Figure 1). Or they may choose to tough it out in the traffic jam, hoping that it will clear up. If the family reaches a road that is currently flooded they can attempt to turn around and go in a different direction. If the family gets caught on a flooded road, the survival of each family member is dependent on their state (e.g. age) and the hydraulic conditions at their location. All of these interactions are simulated during an LifeSim model iteration. Because warning times and people's behavior are sampled from a range of possibilities, the same family may take longer to get warned or choose to remain in their home during the next model iteration.
Simulation results for existing conditions and alternatives can be visualized using LifeSim animation capabilities. In the LifeSim results animation image shown in **Figure III-135**, structures and cars caught (inundated) by floodwaters are red. Yellow structures indicate that a warning was received but the people inside haven't started evacuating yet, and brown structures indicate that a warning hasn't been received yet. Blue cars represent

people mobilizing on roads, and are tracked throughout the study area based on traffic simulation algorithms.

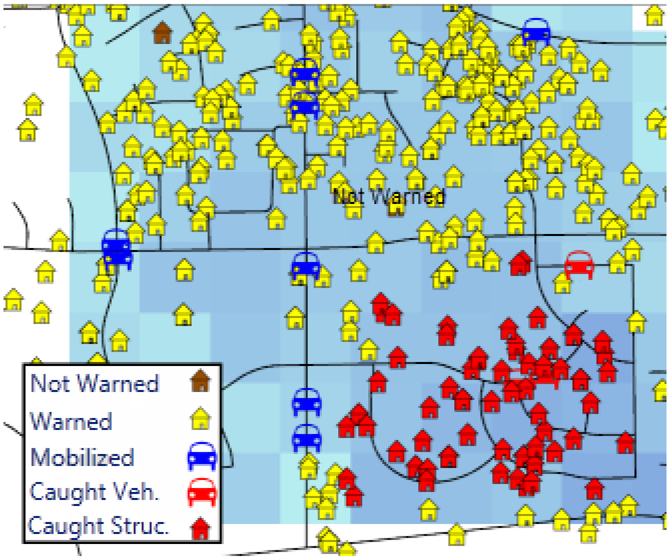

Figure III-135. Example LifeSim Animation

By tracking individual people and their movements, LifeSim can help identify where people are most at risk of losing their lives, whether it is on roads or in structures. We can now pinpoint the locations of greatest potential life loss, which is useful when developing alternative project formulations. For example, a simulation may show that life loss on a particular road is significant. LifeSim allows for a detailed analysis of a range of alternatives based on both structural and nonstructural measures for reducing potential life loss. Nonstructural measures to reduce life loss could include raising or closing at risk road embankments and increasing road capacities to reduce congestion. A nonstructural alternative could also consist of increasing the warning time through better warning issuance and community awareness.

Rather than presenting the entire LifeSim methodology from a theoretical basis, which would be largely repetitive from the simplified LifeSim approach described above, the following example is used to illustrate the full version of LifeSim.

Example LifeSim Application

Introduction

"Herbert Hoover Dike (HHD) is an earthen dam impounding Lake Okeechobee, the nation’s second largest lake. HHD was constructed by hydraulic dredge and fill methods by private and public entities between the early 1900’s and the late 1960’s, initially to provide agricultural water supply. Following major hurricane disasters in 1926 and 1928, Congress authorized USACE to construct elevated embankments at the north and south of the Lake to provide flood protection. In the 1960’s, the Lake was completely encircled with approximately 143 miles of dike and tie-back levees.

Prior to 1978, the Lake conservation pool was generally managed between 12.7 and 14.2 ft. (NAVD88). In 1978, the conservation pool was raised to 17.2 ft. (NAVD88) to meet water supply needs. Indications of excessive seepage and piping were first noted beginning in the early 1980’s. Conditions worsened with time, particularly following years in which lake elevations alternated between extreme high and low levels. To enhance the Lake ecology, and recognizing the risk imposed by the deteriorating condition of the Dike, the Lake Okeechobee Regulation Schedule (LORS), implemented in 2008, lowered the conservation pool upper limit to 15.95 ft. (NAVD88).

Due to the length of HHD, management of the system as well as studies on risk remediation alternatives required USACE Jacksonville District to subdivide HHD into eight reaches. The delineations of each reach were based on factors such as physical characteristics of the dike, foundation conditions, drainage features, and location of population centers. The reach number also corresponded with what District engineers considered to be the priority for remediation. That priority has shifted slightly since due to increased knowledge about each reach. Reach 1 is currently undergoing remediation as it was identified as the highest priority risk on the Dike.

As shown in **Figure III-1-36**, Reaches 2 and 3 represent approximately 30 miles of HHD, with the City of Clewiston and town of Moore Haven adjacent to Reach 2 and the towns of Lake Harbor, South Bay, and Belle Glade adjacent to Reach 3. Clewiston is immediately adjacent to the dike and the other towns are in close proximity. A major highway and hurricane evacuation route (US-27) parallels HHD for approximately 12 miles immediately adjacent to the dike along portions of Reach 2 and 3. Approximately 1,500 square miles of agricultural lands, known as the Everglades Agricultural Area (EAA), lie to the south of the Lake.

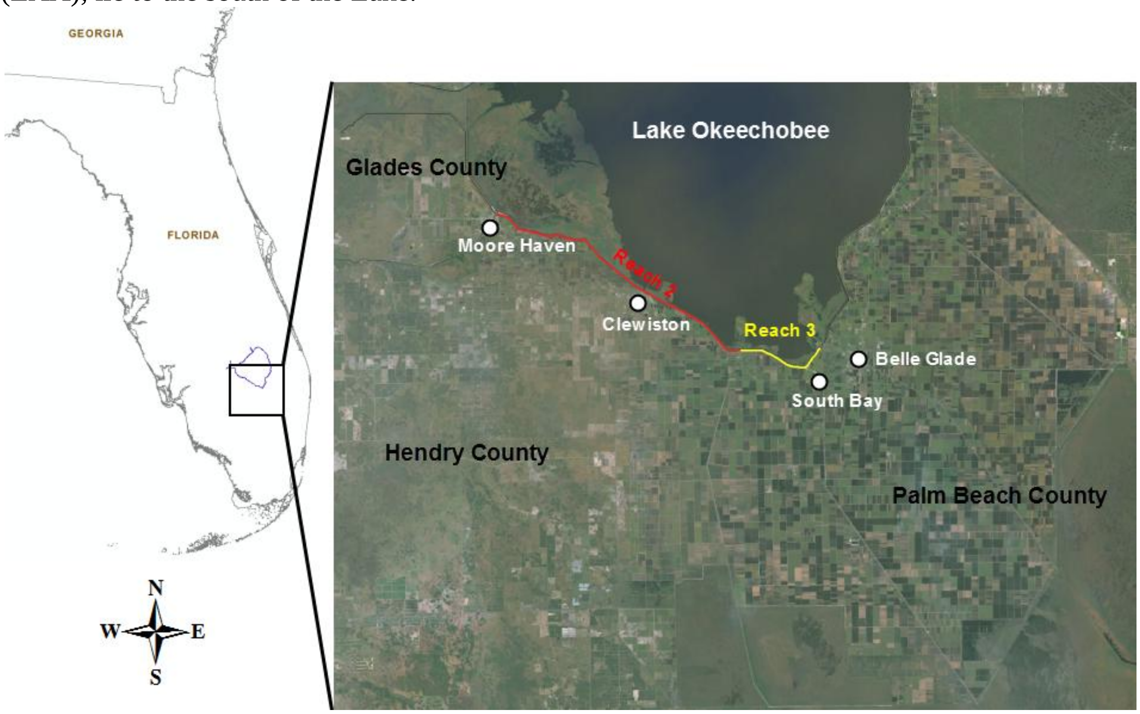

Figure III-1-36. Herbert Hoover Dikes study area

To account for the impact of varying breach location on the consequences for this analysis, reaches 2 and 3 were divided into seven consequence sub-reaches. Delineation of the consequence sub-reaches was done so that any breach within each sub-reach would produce, for practical purposes, the same consequence. To that end, the sub-reaches were delineated by taking into account consequence centers (developed city boundaries from areal imagery), topography, and major flow impediments. The actual location of the breach within a consequence sub-reach was chosen based on the estimated worst-case scenario. Figure III-1-37 illustrates the consequence sub-reaches for this study.

Figure III-1-37. Consequence sub-reaches for the Herbert Hoover Dike study.

LifeSim: Population at Risk (PAR)

LifeSim requires an estimate of the spatial and temporal distribution of population at the time of the initiation of the first evacuation warning for a specific failure scenario. To facilitate gathering these data, LifeSim uses readily available data. Specifically, LifeSim was built to gather this information from the extensive database that accompanies FEMA's HAZUS-MH software program. The HAZUS database includes a polygon shapefile that delineates census blocks for an area as well as the population and building characteristics for each of those census blocks. The spatial and temporal population distribution is described in the following sections.

Population Distribution - Spatial

Most all of the populated areas in the study area are located near Herbert Hoover Dike. The populations of these four incorporated population centers are presented in Table III-1-7. The area covers portions of Palm Beach, Hendry, and Glades Counties. The total estimated population in Reaches 2 and 3 in 2000 was estimated to be 37,523 persons.

Table III-1-7: Annual Estimates Population for Incorporated Places in Florida

Geographic Area	Population Estimates		
	July 1, 2008	July 1, 2004	July 1, 2000
Belle Glade city	15,423	15,456	15,249
Clewiston city	7,173	6,962	6,486
Moore Haven city	1,751	1,728	1,659
South Bay city	4,059	4,038	3,859

Source: Population Division, U.S. Census Bureau

The census block data set used for HHD is based on the information provided with the FEMA HAZUS-MH software [FEMA 2003]. The data set contains most of the required population and demographic information required to run LifeSim. HAZUS database version 1.3 was used in for this analysis. A subsequent release (version 1.4) of the database was made by FEMA midway through the study. Inputs for this specific study area were compared between the two versions, and no appreciable differences were discovered.

For each breach location, only those census blocks that were inundated within the first 20 hours after breach were included in the LifeSim model for a given scenario. The assumption is that after 20 hours, all PAR in the potential inundation zone that would otherwise be unable or choose not to evacuate would be assisted or convinced to leave their residence. Emergency planning zone (EPZ) fields were added to the default HAZUS database to meet requirements of the LifeSim software. The EPZ field allows LifeSim to indentify different warning and mobilization relationships for communities in the flooded area.

Populations were adjusted from the default year 2000 populations provided in the HAZUS database to 2008 estimates from the University of Florida Bureau of Economic and Business Research. Adjustments were made on a community-by-community basis by multiplying the population in all census blocks located in a community by the appropriate factor to reach the year 2008 estimates for that community.

Migrant worker information was provided by Jacksonville District for Hendry and Palm Beach counties. The information included migrant housing locations and capacities. These values were added to the night time (2 am) residential population for the census block where they are located. For daytime, migrant populations were spread evenly to census blocks within the study area that contained agricultural fields which were identified using areal imagery. A total of 4,741 migrant workers were added to the day and night census information for Hendry and Palm Beach counties.

For all flood scenarios where the breach occurs at or above 20 ft. NAVD88, the starting population for all census blocks was reduced by 30%. This pre-breach evacuation assumption is based on the following statement from the HHD Emergency Action Plan (June 2008): "If EL 21.5 ft. NGVD29 is reached without rehabilitation, recent engineering studies indicate that failure would be certain" (Elevation 21.5 ft. NGVD29 is equal to 20.2 ft. NAVD88.). Hence, we assumed that an evacuation order would be in effect until the lake level dropped back below EL 20 ft. NAVD88.

The value of 30% for the pre-breach evacuation is based on various sources of information. The Palm Beach County HHD Emergency Evacuation Guidance Document (PBCDEM 2006) states that "It is projected that approximately 40-70 percent may comply with a mandatory evacuation order when issued prior to a hurricane." The mean of this value was originally chosen because no further information was available. However, there was some concern that this number might not be realistic for Glades and Henry Counties. The socioeconomic and demographic characteristics of those counties are significantly different than Palm Beach County, and even the communities within Palm Beach County that are affected by HHD are not representative of the majority of that county. Therefore, additional information was obtained through interviews with local and county emergency responders and city officials in the towns of Clewiston and Belle Glade. They provided estimates between 5% (Clewiston) and 40% (Belle Glade) for the number of people that would leave if given an evacuation order related to imminent failure of HHD. Due to the relevant local experience and expertise of these officials, the team considered that a number in the range of 5% and 40% would be a more realistic estimate of the pre-evacuation response rate. As a result of this information and the previously documented information, 30% was selected as the most realistic *average* estimate of the pre-breach evacuation response rate.

Population Distribution – Temporal

Variations in the number of people within the flooded area throughout the day can have a significant effect on loss of life. Moreover, the activities that people are engaged in can affect the efficiency at which the warning spreads through an area. Accordingly, LifeSim is designed to take into account both 1) the distribution of people among census blocks throughout the inundated area based on time of day and 2) estimates in the percentage of population involved in various activity types including: at home, outdoors, working/shopping and in transit.

To capture the variation in population and resulting variation in potential life loss at different times of day, estimates of life loss were computed for breaches occurring at 12 different times of day for this study. The 12 times of day used were midnight, 0200, 0400, 0600, etc. To determine the number of people in a census block at any given time, LifeSim pulls relevant data from the HAZUS-MH database. The HAZUS-MH database contains three time-of-day activity distributions. These distributions are as follows: 0200, representing night time; 1400, representing day time; and 1700, representing commuting time. LifeSim takes the data and uses relationships to calculate the number of people in each occupancy class on the census block level.
Variables used in distributing people are as follows:

- Census block population taken from census data stored in HAZUS-MH database
- Daytime residential population inferred from census data
- Nighttime residential population inferred from census data
- Number of people commuting inferred from census data
- Number of people employed in the commercial sector
- Number of people employed in the industrial sector
- Number of students in grade schools (K-12)
- Number of students on college and university campuses in the census tract
- Number of people staying in hotels in the census tract
- A factor representing the proportion of commuters using automobiles, inferred from profile of the community (0.60 for dense urban, 0.80 for less dense urban or suburban, and 0.85 for rural). The HAZUS-MH default value is 0.80.
- Number of regional residents who do not live in the study area, visiting the census tract for shopping and entertainment. The HAZUS-MH default value is zero.

LifeSim interpolates the estimates obtained by applying the HAZUS-MH population data for the three HAZUS-MH time-of-day distributions to obtain estimates for every two-hour interval throughout a 24-hour period. **Figure III-1-38** illustrates the fluctuation of population at risk within the 20-hour inundation boundary for a breach in consequence sub-reach 2 point 5. (Breaches at pool elevations of 14 ft. and 17 ft. NAVD88 do not cause inundation of populated areas, hence the 0 population at risk for those elevations.) This temporal distribution suggests that a large percentage of the population leaves the area during the day and returns at night.

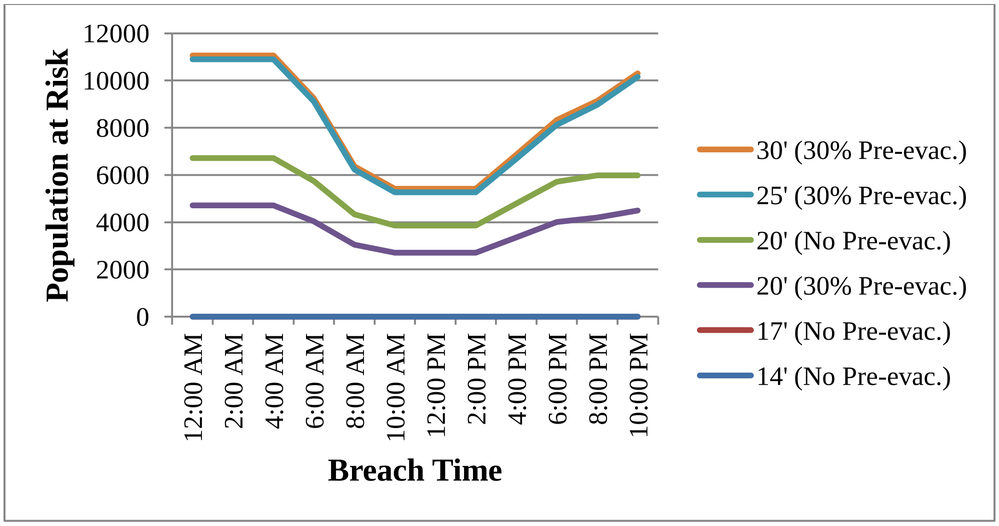

Figure III-1-38. Population distribution by time of day for breach at reach 2 point 5.

Population estimates for each of the four LifeSim activity types are then computed using the mapping shown in Table III-1-8.

Table III-1-8. Mapping of HAZUS-MH occupancy classes to LifeSim activity types.

LifeSim activity type	HAZUS occupancy class
Residential-indoors	Residential-indoors Hotels-indoors
Outdoors	Residential-outdoors Hotels-outdoors
Working/shopping	Commercial-indoors Commercial-outdoors Industrial-indoors industrial-outdoors Education-indoors Education-outdoors
In transit	Commuting-own car Commuting-public transportation

Finally, population is distributed among activity types using a set of activity factors. These values are based on research from research by Rogers and Sorensen in 1988. Their research described how a given warning system has a penetration capability that can be distinguished for the following five fundamental locations or activities:

1. Home asleep
2. Indoors at home or in the neighborhood
3. Outdoors in the neighborhood
4. In transit
5. Working or shopping

They also added two other activities: “watching television” and “listening to radio,” which override the first set of five locations or activities.

LifeSim: Loss-Of-Shelter Module

The loss of shelter module categorizes buildings, which people might use for protection from the effects of flooding, into one of three flood zone categories that are used for estimation of fatality rates. Buildings are classified based on structure type. Each building classification is defined by main materials used and type of construction, and height which is represented through the number of levels in the building.
Loss of shelter categories for buildings are defined according to the damage caused by flood water. The basic factors that affect loss of shelter are:

1) Building type
2) Number of levels in the building
3) Water depth
4) Flow velocity

The first two factors are attributes of the building classification. Partial or complete destruction of a building will vary based on both building type and water depth and velocity. The range of damage due to depth and velocity depends on the type of construction as well as the number of stories. Heavy buildings, such as masonry or concrete, have a higher resistance to destruction or floatation in a flood than lightly constructed wood buildings. Buildings that are anchored to their foundations have a higher resistance than unanchored buildings. The criteria for structural damage used in this analysis are displayed in Table III-1-9.

Table III-1-9. RESCDAM recommended building damage criteria

Building type	Partial damage	Total damage
Wood-framed		
unanchored	$v*d \geq 2\ m^2/s$	$v*d \geq 3\ m^2/s$
anchored	$v*d \geq 3\ m^2/s$	$v*d \geq 7\ m^2/s$
Masonry, concrete & brick	$v \geq 2$ m/s & $v*d \geq 3\ m^2/s$	$v \geq 2$ m/s & $v*d \geq 7\ m^2/s$

Once damage to the building caused by depth and flow velocity has been calculated, the module then calculates the submergence for each level of the building based on user-defined submergence criteria. Submergence is defined as a water level inside the building that makes survival very unlikely. Unlike structural damage, which is defined as a state that applies to the building as a whole, submergence is defined for each level of the building separately.

Submergence value results in the loss-of-shelter category for each level in each building type and height category that might exist. Loss of shelter categories are then assigned to flood (lethality) zones, for which historical fatality-rate probability distributions were estimated by McClelland and Bowles. Flood zones distinguish physical flood environments in which historical rates of life loss have distinctly differed. Three flood zones are physically defined by McClelland and Bowles by the interplay between available shelter and local flood depths and velocities, summarized as follows:

- *Chance zones* in which flood victims are typically swept downstream or trapped underwater and survival depends largely on chance; that is, the apparently random occurrence of floating debris that can be clung to, getting washed to shore, or otherwise finding refuge safely. Historical fatality rates range from about 50 percent to 100 percent, with an average rate of about 90 percent.
- *Compromised zones* in which the available shelter has been severely damaged by the flood, increasing the exposure of flood victims to violent floodwaters. An example might be when the rooms inside a building experience rapidly-moving shoulder-height flood water. Historical fatality rates range from zero to about 50 percent, with an average rate of about 10 percent.
- *Safe zones* are typically dry, exposed to relatively quiescent floodwaters, or exposed to shallow flooding unlikely to sweep people off their feet. Examples might include the second floor of residences and sheltered backwater regions. Historical fatality rates are virtually zero.

Debris in flood water can have a damaging effect on buildings, vehicles, and people. However, the effects of debris are not explicitly considered in LifeSim.
For this analysis, the loss of life analysis was computed on a census block level. The number of buildings in a census block is obtained from the HAZUS-MH data, which is categorized into the different building types and numbers of levels. The loss of shelter estimates are applied to the number of buildings in each building type under the assumption that the buildings are uniformly distributed throughout a census block.

The submergence criteria for each level in a building used in this analysis are displayed in **Figure III-1-39** and Table III-1-10. LifeSim is setup to allow people below the age of 65 to climb to the highest level of residential buildings, which is the roof for all structure types other than mobile homes. For people above the age of 65, LifeSim places them in the highest level below the roof. (The number of PAR above age 65 is provided in the HAZUS census data). For basements, submergence is considered to occur for any water level above the ground surface. For non-residential buildings, LifeSim was set up to allow people to move to the top floor, but not onto the roof. The first floor level is determined based on typical foundation heights in the study area, while the levels of other floors are estimated based on the first floor level and a standard floor height. Foundation heights were set to 0 ft. (slab on grade) for all structures in this study as determined by visual inspection (Google Earth Street View) and information from Jacksonville District.

In case of partial building damage, flood water can move into the building through a knocked down wall or window. People inside the building are exposed to a flow of water that might be capable of sweeping them out of the building into the open flood. Loss-of-shelter category is decided in this case based on water depth and velocity inside each level in the building compared to human stability criteria.

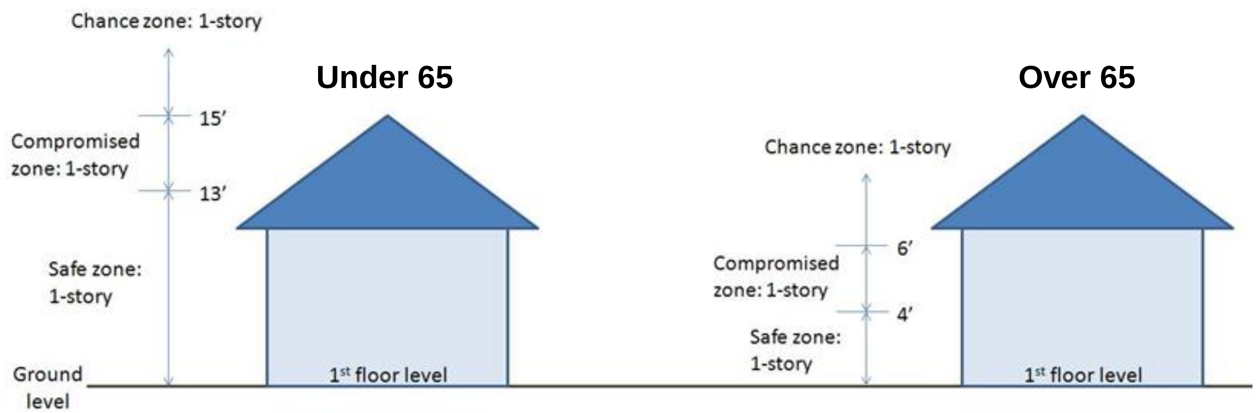

Figure III-1-39. LifeSim Submergence Criteria - 1 Story Residential Structure.

Table III-1-10. Submergence Criteria used in Herbert Hoover Dike LifeSim application.

			Age < 65		Age > 65	
Occupancy type	**Description**	**Number stories**	**Comp. Zone Start (ft)**	**Chance Zone Start (ft)**	**Comp. Zone Start (ft)**	**Chance Zone Start (ft)**
RES2	Manufactured Home	1	4	6	4	6
RES3 – RES6	Multi Resident Living	2	13	15	13	15
COM1 – COM3	Trade and personal service	1	4	6	4	6
COM4 – COM7	Financial/Professional/Technical/Medical	2	13	15	13	15
COM8 – COM9	Entertainment, Theaters & Recreation	1	4	6	4	6
COM10	Parking	2	13	15	13	15
IND1 – IND6	Heavy/Light Industry	1	4	6	4	6
AGR1	Agriculture	1	4	6	4	6
REL1	Church	1	4	6	4	6
GOV1 – GOV2	General Services/Emergency	1	4	6	4	6
EDU1 – EDU2	Schools /Colleges	2	13	15	13	15

LifeSim – Warning and Evacuation Module

The three major components in the LifeSim Warning and Evacuation Module are summarized in the following subsections.

Warning

The warning initiation time is the time at which an evacuation warning is first issued to the PAR. It is defined to be positive if the warning is issued after dike failure occurs, or to be negative if the warning is issued before failure occurs. For this analysis, warning initiation times were determined through expert elicitation with District staff involved with this risk assessment activity. Dike failure in this instance is defined as the time when weir flow begins through a breach in the dike. Warning issuance times relative to dike failure are shown in Table III-1-11 for each failure mode.

Table III-1-11. Warning issuance times relative to time of failure in HHD LifeSim analysis.

			Warning issuance times relative to time of failure	
	Failure Mode	**Stillwater Elevation (NAVD88)**	**Day (hrs)**	**Night (hrs)**
Pre-evacuation	All failure modes	≥ 20 ft.	-1.5	0
No pre-evacuation	Overwash failure	< 20 ft.	-1.5	0
	Overtopping failure			
	Piping through embankment failure (IM13)			
	Flood wall instability failure			
	Piping through foundation failure (IM22)	< 20 ft.	-0.5	0
	Embankment slope stability failure			
	Piping along conduit failure (IM17)			
	Piping into conduit failure (IM18)			
	Piping along wall failure (IM19)			

The rate at which the warning is received throughout an area is represented in LifeSim using a warning diffusion curve, which is the cumulative percentage of the PAR that receives the warning message versus time where time 0 is the warning initiation time. The overall area to be warned for a breach of HHD was divided into multiple emergency planning zones (EPZs), delineated on county lines, based on the type of warning systems available. Empirical warning diffusion curves are available in LifeSim for a range of different types of warning systems and different time-of-day activities.

The Herbert Hoover Dike Emergency Evacuation Guidance Document (PBCDEM 2006) states that notification to evacuate the area will be provided through the Emergency Alert System (TV and Radio), NOAA Weather Radios, Direct Notification (fire and emergency service staff) and the Emergency Information Center (call in). **Figure III-1-40** illustrates the Emergency Alert System (EAS) warning efficiency for different times of day, where the time of day represents the time at which the EAS is initiated. These are developed by taking into account the variation in activates that people are engaged in throughout the day.

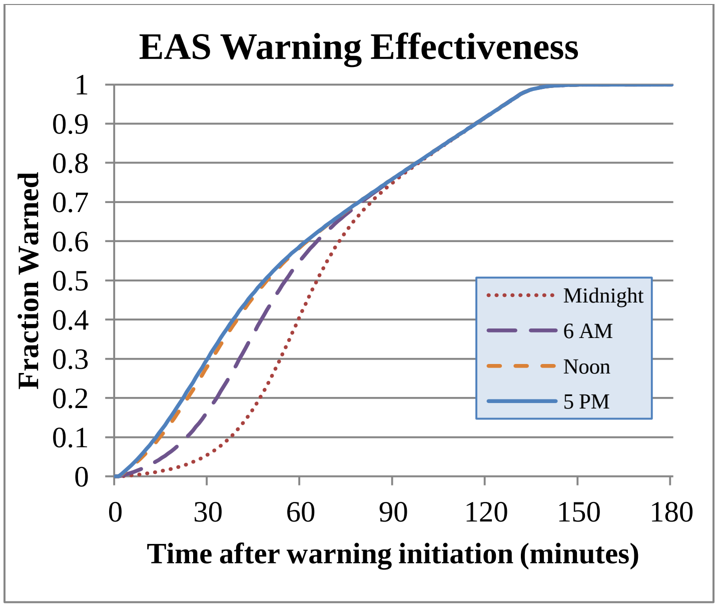

Figure III-1-40. EAS warning effectiveness curves for different initiation times.

Additionally, Palm Beach County maintains a dialogic telephone call-out system (all listed numbers included on call list, unlisted numbers and cell phones must register with the county to be on the call list), Mobile AM Radio Stations, and an internet web site that will be used to assist with spreading the evacuation order. The warning diffusion curves for the Palm Beach County EMA are displayed in **Figure III-1-41**.

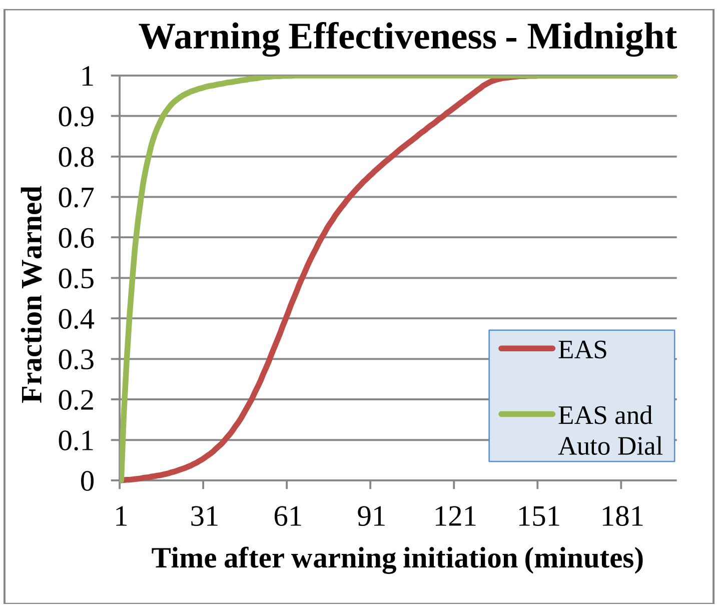

Figure III-1-41. Warning diffusion curves for EMA downstream of HHD reaches 2 and 3.

Mobilization

After receiving the warning message, people who are willing and able to leave will prepare to leave. The rate of mobilization is represented in LifeSim using a mobilization curve, which is a cumulative percentage of the warned PAR that starts moving away from the area of potential flooding towards safe destinations. A mobilization curve represents two important pieces of information: (1) how long it takes people after they received a warning to leave their home, and (2) what percentage of the population will not mobilize (1 minus the maximum mobilization %). Typically a mobilization curve will not reach 100% until enough time has passed to allow emergency responders to physically enter every home and remove people that are either unable or unwilling to mobilize on their own.

For all breach scenarios with a pool elevation greater than or equal to 20 ft. NGVD88, the starting population is reduced by 30% to account for pre-evacuation as described above. For the maximum mobilization, approximately 20% of the population was estimated to either choose not to evacuate or be unable to evacuate within the first 20 hours after the breach. This value is based on information from multiple interviews with local emergency responders. It represents the fact that flooding does not reach the populated areas typically for at least one hour after the breach occurs. During that time, not only will a more urgent evacuation order be issued, but TV and News stations will have started broadcasting images of the breach. These additional warnings will greatly increase the maximum mobilization. We also assumed that during the high pool scenarios where 30% of the population already evacuated, that emergency personnel would be able to mobilize those people that could not mobilize on their own, and only the people that choose not to mobilize would remain in the area. We estimated that to be 89% of the remaining population through conversations with local emergency responders. We also assumed that the decision to mobilize would be quicker for people if they were already alerted to the fact that HHD was in danger of failing. Therefore, the timing of the mobilization relationship for the high pools was reduced significantly as shown in Figure III-1-42.

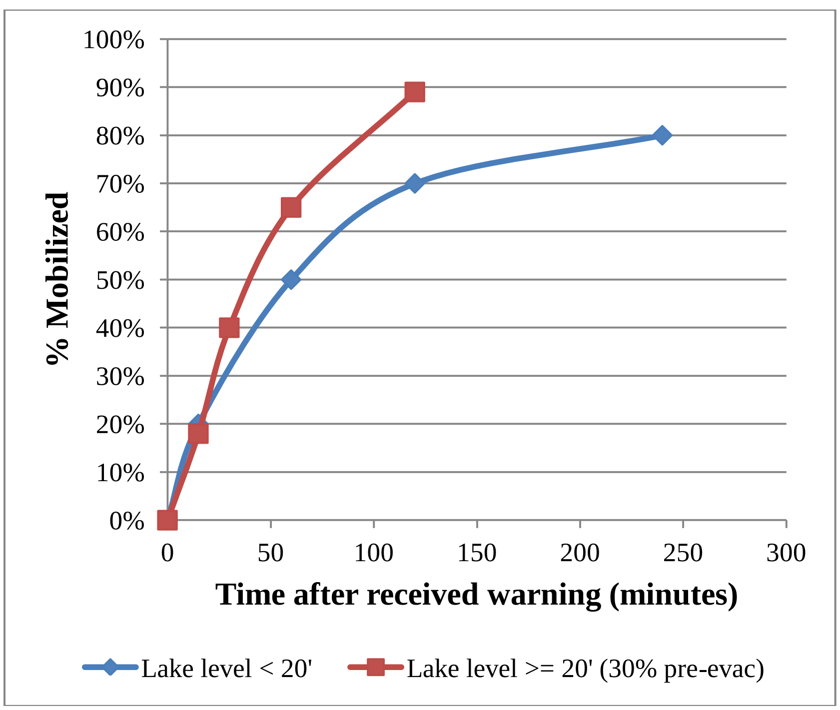

Figure III-1-42. Mobilization curves used in HHD LifeSim analysis.

Evacuation-Transportation

The evacuation-transportation process commences with mobilization and ends with either clearance of the flooding area or entrapment if the evacuation route becomes blocked by flooding. People who clear the flooding area are assigned to a “safe” flood zone and people who are trapped on the road are assigned to a flood zone that depends on their mode of evacuation and the most severe flooding conditions for the event.

Three modes of evacuation are included in LifeSim: cars, sports utility vehicles (SUV’s) and pedestrians. The following distribution of evacuation modes was determined through discussions with USACE Jacksonville District staff: Passenger car (50%), Trucks (50%), pedestrian (0%). 0% was chosen for pedestrian evacuation due to the large distances that people would be required to cover to get to safety if HHD was to fail (i.e. no evacuation destinations are inside the inundated areas and the inundated areas are extremely large). LifeSim was also configured with the assumption that an average of three people would occupy each evacuating vehicle.

The Greenshield [1935] transportation model is used in LifeSim to represent the effects of traffic density and road capacity on vehicle speed. The original model was modified to represent congestion and traffic jams by introducing a minimum “stop-and-go” speed (Vjam) if the jam density (Djam) for a road class is exceeded. Each road class is assigned default values of the number of lanes, free flow speed (ffs), Djam and Vjam based on the Highway Capacity Manual (HCM) [TRB 2000], although these can be overridden if more detailed information is available for the road system.
A GIS road network polyline shapefile was obtained from the USGS web site that contained most roads in the area. It also contained the data required by LifeSim to determine number of lanes, free-flow speed, jam density, and a minimum “stop and go” speed. The USGS road network was modified on a case-by-case basis as necessary to repair the original data when obvious errors were encountered that had a significant impact on traffic movement during the evacuation process. Generally, missing road segments were added by referencing areal imagery.

A GIS point shapefile represents a set of safe destinations for evacuees to go. LifeSim models the movement of people to destination points using the shortest route available. People who reach a safe destination are considered as the “cleared” group. Safe destination locations were carefully defined to represent the expected evacuation situation in each scenario. Designated routes in evacuation traffic management plans were used to assess the likely evacuation routes. Evacuation destinations were placed just outside the maximum inundated area on the main evacuation routes that would be used by people to leave the flooded area. No evacuation destinations are located within the flooded area. The actual shelters are located far away from the flooded area in most cases, and the assumption is that people would proceed to those shelters after getting out of immediate danger from the dike breach.

LifeSim – Loss-of-Life Module

The final step in LifeSim is the estimation of loss of life. Previously described modules simulate the spatial redistribution of people existing within the study area through the processes of warning and evacuation and assign loss-of-shelter category/flood zones based on the effect of flood water on the buildings, vehicles and pedestrians throughout the study region. These results are combined in the Loss-of-Life (LOL) Module with the probability distribution of fatality rates for each loss-of-shelter category/flood zone to obtain estimates of the expected number of fatalities within the study area. For this analysis, the expected value (mean) of the fatality rate distributions developed by McClelland and Bowles [2000], updated Aboelata et al [2003] and displayed in **Figure III-1-43** were applied. The mean values for the safe, compromised and chance flood zones are 0.0002, 0.1200, and 0.9145, respectively.

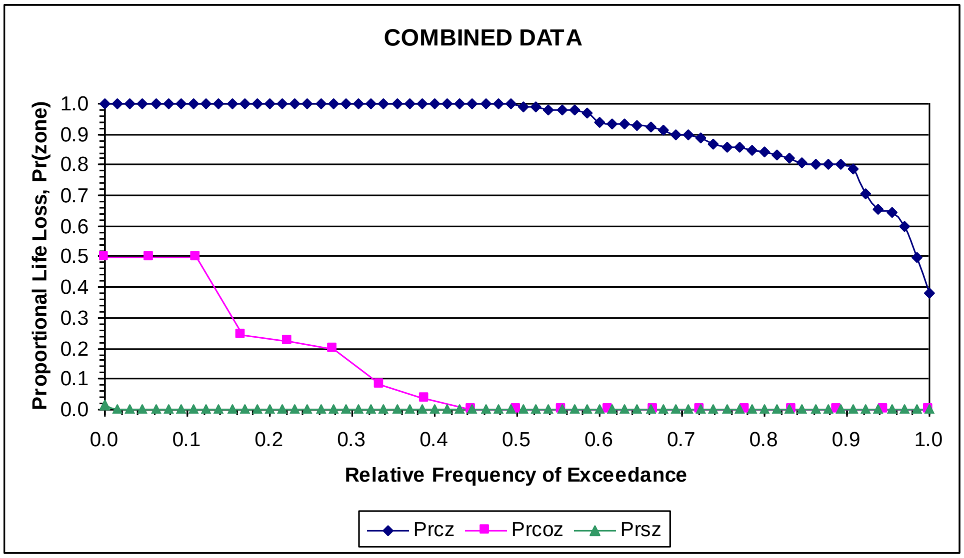

Figure III-1-43. Probability distributions for fatality rates for each flood zone.

LifeSim – Results

Given the nature of this analysis, most of the results are considered "For Official Use Only" (FOUO) and therefore not included explicitly in this report. Results were computed for the full range of potential lake elevations and times of day. In total, six different lake elevations were run at 12 different times of day at each seven breach locations. This resulted in a potential requirement to run 504 different simulations of LifeSim. However, the dike breach modeling showed that for many of the lower lake levels, a breach would not inundate populated areas. Therefore LifeSim was not run for those scenarios and the total number of runs was almost cut in half. The time required to run a single simulation in LifeSim ranged from 5 to 120 minutes. Multiple computers were utilized to allow for simultaneous processing of results.

Breach location 3.1, which takes place in Palm Beach County, has a relatively low loss of life to population at risk ratio due to the existence of the advanced warning system. Palm Beach County has a robust warning system in place that includes emergency alert and autodial reverse 911. The improved warning allows people to mobilize and evacuate earlier than would be the case for a less effective warning system, e.g. EAS only. Breach locations 3.2, 3.3, and 2.4 yielded roughly the same results. Like breach location 3.1, the flood takes place in Palm Beach County which has the better warning system than Glades and Hendry Counties. These locations are sufficiently far away from the main population center (Belle Glade) to cause flooding in that city within the first 20 hours after breach. The town of South Bay just southeast of the breaches does get inundated in the first 20 hours. However, the time between breach and arrival in South Bay combined with the fact that South Bay is a relatively small town yields a small estimated loss of life for each pool height. Breach location 2.4 is far enough west to start affecting the town of Clewiston, which is in Hendry County. The inclusion of Clewiston for breach location reach 2.4 led to slightly higher PAR and life loss than locations 3.2 and 3.3.

As expected, breach location 2.5 has the highest estimated life loss and PAR in the study. The breach occurs at the town of Clewiston, which is right next to the dike. The highest life loss occurs at night. This is due to the fact that the majority of people during that time are home asleep. Since the warning system in the area is EBS, a significant portion of the population is not getting warned early enough to allow for safe evacuation. A breach at reach 2 point 5 with a 30 ft. pool height at night represents the worst case scenario for this study.

Another observation when looking at results of a breach at location 2.5 is that life loss with no pre-evacuation (lower pool levels) stays relatively small. This indicates that if the breach occurs at high pool levels, then the inundation event will sweep through Clewiston quickly and not allow the PAR to mobilize. If the breach occurs at lower pool levels, then the flood will move slowly giving people more time to evacuate.
Breach location 2.6 occurs between the towns of Clewiston and Moore Haven. Like 2.5, the highest life loss occurs at night. Since the breach occurs between two towns, the bulk of the flood does not reach populated areas within the first 20 hours resulting in a much lower PAR.

Breach location 2.7 occurs at the town of Moore Haven. By nature of the flooding that would occur at this location and the smaller size of the town in comparison to Clewiston a far lower loss of life was estimated than reach 2.5. The town of Moore Haven has a large canal going through it that can hold a portion of the flood as the breach occurs. This allows the inhabitants valuable time to evacuate. Also, Moore Haven is located farther away from the dike than Clewiston, which also lends more time to the inhabitants to evacuate.